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Effect of anhydrous ammonia and broadcast-applied phosphorous and potassium on soil chemical properties in conservation tillage systems

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EFFECT OF ANHYDROUS AMMONIA AND BROADCAST-APPLIED PHOSPHORUS AND POTASSIUM ON SOIL CHEMICAL PROPERTIES IN CONSERVATION TILLAGE SYSTEMS

Iowa State University PH.D. 1986

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Effect of anhydrous ammonia and broadcast-applied phosphorus and potassium on soil chemical properties in conservation tillage systems

by

Susan Gatter Robbins

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INTRODUCTION

The type of tillage used by a farm operator has a significant effect on the physical, chemical, and biological properties of the soil. In 1984, over 40 million crop ha in the United States were under some form of conservation tillage management (Conservation Tillage Information Center, 1985). With the ever-increasing use of conservation tillage practices by crop producers, it is essential that the tillage-induced changes in soil properties be assessed.

In conventional tillage systems, the upper 15- to 20-cm of soil is thoroughly mixed, whereas in conservation tillage systems minimal disturbance of soil occurs. With respect to nitrogen (N) fertilization, the resultant effect is the formation of a thin, highly acidified surface layer where N has been surface applied in reduced tillage systems. Without mechanical incorporation of the fertilizer, acidity produced by nitrification of applied N remains concentrated in the upper approximate 5 cm of soil (Triplett and Van Doren, 1969; Moschler et al., 1973; Blevins et al., 1977; Fox and Hoffman, 1981; Mahler and Harder, 1984). Furthermore, Blevins et al. (1977) and Dick (1983) have observed lower pH values not only at the soil surface but throughout the soil profile (to 30-cm depth) in no-till soils compared to tilled soils with surface-applied N.

Although acidification by surface broadcast N fertilizers in no-plow systems has been well documented, little data have been reported on the acidifying effects of subsurface banded N applications, such as anhydrous ammonia (NH_3), in conservation tillage systems. A widely used

source of N, NH_3 represented 35% of the total N fertilizer applied in the United States in 1984 (Hargett and Berry, 1985). Increased usage of NH_3 in the future is likely as research findings have indicated a greater N efficiency and higher yields in no-till systems with subsurface N banding, as compared to surface broadcast applications (Mengel et al., 1982; Touchton and Hargrove, 1982). The reduced N uptake observed with surface-applied N in no-till systems may be caused by increased N immobilization in decomposing surface residue and/or greater NH_3 volatilization at the soil surface. Recently, Evangelou and Blevins (1985) suggested that a preferential attraction for K^+ over NH_4^+ on the cation exchange sites specific to no-till surface soils could result in greater N losses. Therefore, these researchers recommended the placement of N below the soil surface. With the growing use of NH_3 in conservation tillage systems, the need for research on the acidifying effects of NH_3 is apparent.

With respect to phosphorus (P) and potassium (K) fertilization in conservation tillage systems, the effect of an undisturbed soil profile is a surface accumulation of these nutrients where P and K fertilizer has been broadcast applied. Without mechanical incorporation of the fertilizer, these relatively immobile nutrients remain concentrated in the upper approximate 5 cm of soil (Shear and Moschler, 1969; Triplett and Van Doren, 1969; Fink and Wesley, 1974; Ketcheson, 1980; Cruse et al., 1983). This finding has created concern that the build-up of P and K at the soil surface may create plant nutritional problems.

Most investigations to determine levels of soil P and K in conservation tillage systems have utilized sampling methods in which core samples are collected with a soil probe at designated surface points across a field and the core samples are then subdivided to represent various depth increments. No research work has been conducted to assess definitively the spatial distribution of soil P and K in conservation tillage management. This information is vital for understanding potential factors affecting nutrient availability in no-plow systems.

The purpose of the work reported in this dissertation was to determine the effects of anhydrous ammonia and broadcast-applied phosphorus and potassium on soil chemical properties in long-term conservation tillage systems. Tillage systems evaluated included ridge till-plant, ridge slot-plant, and flat no-till systems.

PART I. EFFECT OF ANHYDROUS AMMONIA ON SOIL pH IN CONSERVATION TILLAGE SYSTEMS

INTRODUCTION

Conservation tillage methods are increasingly being used by crop producers throughout the United States. By 1984, over 40 million crop ha were under some form of conservation tillage management in the United States (Conservation Tillage Information Center, 1985). The adoption of such practices by farmers has created pronounced changes in the physical, chemical, and biological properties of soils. Blevins et al. (1983), among others, have shown that soil pH, which is an important parameter influencing crop yields, may be altered significantly by the type of tillage employed.

In conservation tillage systems minimal disturbance of soil occurs, whereas in conventional tillage systems, the upper 15- to 20-cm of soil is thoroughly mixed. The resultant effect is the formation of a thin, highly acidified surface layer where N has been surface applied in reduced tillage systems. Without mechanical incorporation of the fertilizer, acidity produced by nitrification of applied N remains concentrated in the upper approximate 5 cm of soil (Triplett and Van Doren, 1969; Moschler et al., 1973; Blevins et al., 1977; Fox and Hoffman, 1981; Mahler and Harder, 1984). Furthermore, Blevins et al. (1977) and Dick (1983) have observed lower pH values not only at the soil surface but throughout the soil profile (0 to 30-cm depth) in no-till soils with surface-applied N when compared to tilled soils.

Although acidification by surface broadcast N fertilizers in no-plow systems has been well-documented, little data have been reported on the acidifying effects of subsurface banded N applicatons, such as anhydrous

ammonia (NH_3), in conservation tillage systems. A widely used source of N, NH_3 represented 35% of the total N fertilizer applied in the United States in 1984 (Hargett and Berry, 1985). Increased usage of NH_3 in the future is likely as research findings have indicated a greater N efficiency and higher yields in no-till systems with subsurface N banding, as compared to surface broadcast applications (Mengel et al., 1982; Touchton and Hargrove, 1982). The reduced N uptake observed with surface-applied N in no-till systems may be caused by increased N immobilization in decomposing surface residue and/or greater NH_3 volatilization at the soil surface. Recently, Evangelou and Blevins (1985) suggested that a preferential attraction for K^+ over NH_4^+ on the cation exchange sites, specific to no-till surface soils, could result in greater N losses. Therefore, these researchers recommended the placement of N below the soil surface.

With the growing use of NH_3 in conservation tillage systems, the need for research on the acidifying effects of NH_3 is apparent. The objective of this research was to determine the magnitude, distribution, and persistence of soil acidity due to the injection of NH_3 in long-term conservation tillage systems that do not disturb the ammonia injection zone.

MATERIALS AND METHODS

Study Areas

Six field locations, each representing a different crop-fertilizer-tillage system, were investigated in 1983 and 1984. Each area has a long-term history of NH_3 application in a conservation tillage system. Areas I and II are located at the Agronomy and Agricultural Engineering Research Center near Ames, IA. For nine consecutive years, Area I has been in a ridge till-plant system and Area II has been in a ridge slot-plant system. A corn-soybean rotation was followed the first five years, and corn has been grown each subsequent year. The soil at both areas is a Webster clay loam (Typic Haplaquoll). Areas III and IV are located at the Frederick farm near Springdale, IA. At both locations, continuous corn under a flat no-till system has been grown on a Tama silt loam (Typic Argiudoll) for the last 10 years. Areas V and VI are located at the Stadtmueller farm near Central City, IA. Under ridge till-plant management for 12 years, both areas were in continuous corn for six years, followed by six years in an intercropping rotation system of alternating 6-row corn and soybean strips. The soil at both sites is a Kenyon loam (Typic Hapludoll). Selected chemical and physical properties of the soils at each field location are shown in Table 1.

Areas I and II were fertilized on 6 May 1983 with NH_3 at a rate of 180 kg N/ha at 75-cm spacing. Comparable rates of NH_3 were applied in the previous years when planted to corn. To evaluate the persistence of acidity with time, Area II was selected for further study in 1984.

Table 1. Chemical and physical properties of soils in areas studied

Depth	CEC[c]	Organic C[d]	Particle size distribution (mm)[a] Sand (2-0.05)	Silt (0.05-0.002)	Clay (<0.002)	Gravimetric water content[b] At -0.03 MPa	At -1.5 MPa
-cm-	cmol(+)kg^{-1}				%-		
			Area I				
0-5	48	3.9	26	46	28	28	21
5-15	49	3.6	27	45	28	29	22
15-25	53	3.1	25	45	30	30	24
			Area II				
0-5	39	3.4	37	40	23	25	18
5-15	41	3.0	33	43	24	26	19
15-25	42	2.5	30	43	27	27	20
			Area III				
0-5	31	2.1	3	73	24	27	18
5-15	31	1.8	2	73	25	26	18
15-25	34	1.2	3	67	30	28	20
			Area IV				
0-5	30	2.6	3	74	23	29	19
5-15	28	1.7	3	71	26	27	18
15-25	29	1.1	2	68	30	29	19

[a]Particle size analysis by pipette method (Walter et al., 1978).

[b]Water content by pressure plate extractor (Soil Survey Staff, 1984; Richards, 1965).

[c]CEC by ammonium saturation method (Chapman, 1965).

[d]Organic C by Walkley-Black method (Allison, 1965).

Table 1. Continued

Depth	CEC	Organic C	Particle size distribution (mm) Sand (2-0.05)	Silt (0.05-0.002)	Clay (<0.002)	Gravimetric water content At -0.03 MPa	At -1.5 MPa
-cm-	cmol(+)kg^{-1}				%-		
			Area V				
0-5	23	2.7	34	47	19	22	15
5-15	22	2.0	34	46	20	20	14
15-25	22	1.7	32	46	22	21	14
			Area VI				
0-5	21	2.4	37	44	19	21	14
5-15	20	1.7	36	44	20	19	13
15-25	21	1.5	33	45	22	21	15

Planted to corn, this area was fertilized with NH_3 at a rate of 180 kg N/ha on 26 April 1984 on only one-half of the field.

Planted to corn, Area III received a starter fertilizer application (80 kg/ha of a 5-10-22 grade) on 28 April 1983 and an NH_3 application (225 kg N/ha at 95-cm spacing) on 10 June 1983. Both Areas III and IV were fertilized at similar rates of NH_3 in the preceding 10 years. In 1983, Area IV was planted to a sorghum-sudan hybrid without N fertilization and was assessed for residual acidity from prior N applications.

A starter fertilizer (225 kg/ha of a 9-10-25 grade) was banded for corn planted on 7 May 1984 at Area V. Anhydrous ammonia was then injected on 12 June 1984 in alternate 90-cm wide interrows at a rate of 145 kg N/ha. Therefore, the N concentration within the zone of application was equivalent to 290 kg N/ha. This rate and placement of NH_3 were used at both Areas V and VI when planted to corn. Planted to soybeans in 1984, Area VI was evaluated for residual effects of the preceding year's N application.

Field Methods and Sampling

At each of the six field locations, six sites were examined and sampled. A trench, extending across a distance of three adjacent crop rows (two interrows), was excavated to expose a vertical section of soil from the soil surface to a 25- to 30-cm depth at each site.

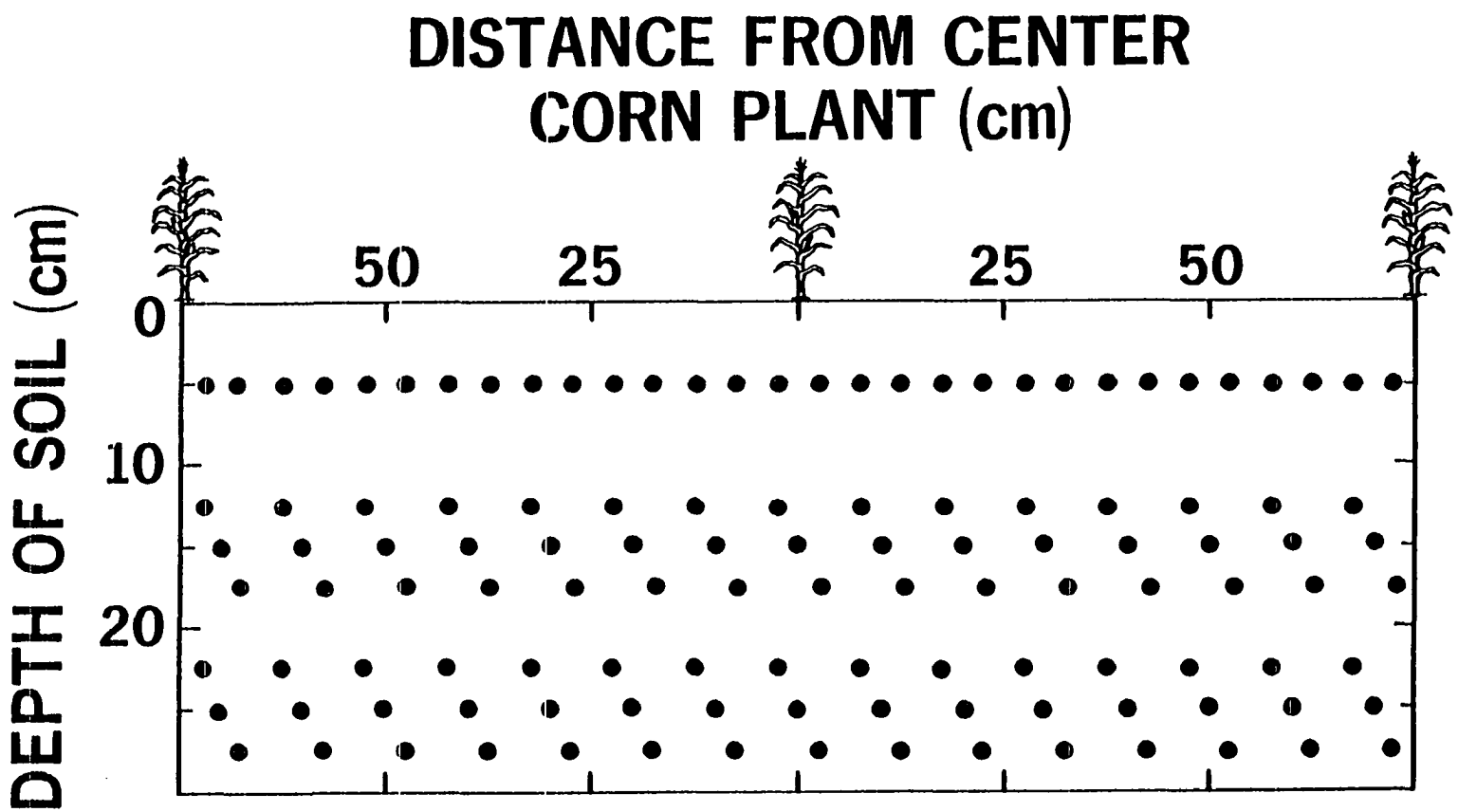
A qualitative colorimetric procedure (Openshaw, 1966) was utilized to visually locate and characterize the acidic zones at a site. Distilled water was applied initially with a plastic hand sprayer in order to uniformly moisten the face of the trench. A suspension of talc in

isopropyl alcohol was then sprayed on the soil face to produce a solid white coating. Finally, a selected pH indicator solution was sprayed on the whitened surface. Use of the pH indicators, bromocresol green or chlorophenol red, produced sharp color contrasts and effectively detected differences in soil pH. Within 10 minutes after the application of the indicator, observations of the size and distribution of acidic zones were recorded and the site was photographed.

Prior to sampling, the talc and indicator were carefully scraped from the surface of the exposed soil layer and a grid was established on the soil face. Each site was then quantitatively sampled by 10-cm horizontal increments and vertical increments of 0 to 5 cm, 5 to 15 cm, and 15 to 25 cm at Area I (July 1983), Area II (July 1983, July 1984), Areas III and IV (August 1983), and 0 to 10 cm, 10 to 20 cm, and 20 to 30 cm at Areas V and VI (July 1984).

To complement the investigation on soil acidity in conservation tillage systems, in situ soil pH measurements were made at Area II in July 1984. Six sites, three which had received N fertilizer and three without N fertilization, were examined in the in situ study. One hundred twenty pH determinations were made on the surface of each exposed soil profile (Figure 1). The soil water potential at the time of measurement approximated field capacity. The measurements of in situ soil pH were performed using a Sensorex Model 450C flat-surface combination pH electrode connected to an Orion Model 407A portable pH meter. In the laboratory, the Sensorex pH electrode had been shown to produce stable reproducible readings of soil pH at water potentials ranging from -1.5 MPa to saturation (Breitenbeck and Bremner, 1984). The readings were

Figure 1. Points of in situ pH measurement at a site


DISTANCE FROM CENTER
CORN PLANT (cm)
50
25
25
50
DEPTH OF SOIL (cm)
0
10
20

highly correlated with those obtained by standard methods. To assess the reliability of the in situ pH measurements, a 1.8-cm diameter core sample was collected for subsequent laboratory analysis at each point of field measurement at the sites receiving N fertilization in 1984.

Laboratory Analyses

With the exception of the core samples collected from the in situ study, all soil samples were analyzed for soil pH using 1:2 soil-water suspensions after a 0.5-h equilibration time. A Fisher universal glass electrode (Fisher catalog no. 13-639-3) and a Fisher calomel reference electrode (Fisher catalog no. 13-639-51) were used with the Beckman Model 3500 pH meter calibrated with certified pH 4.0 and pH 7.0 buffer solutions (Fisher Scientific Co.).

Analyses of the core samples collected from the in situ study were performed with the Sensorex flat-surface combination pH electrode on saturated soil pastes and with the Fisher bulb-type glass and calomel reference electrodes on 1:1 soil-water suspensions, 1:2 soil-water suspensions, and 1:2 soil-0.01M $CaCl_2$ suspensions.

Contour lines for soil pH were obtained by using the CONTR 2 program that is available at the Iowa State University Computation Center.

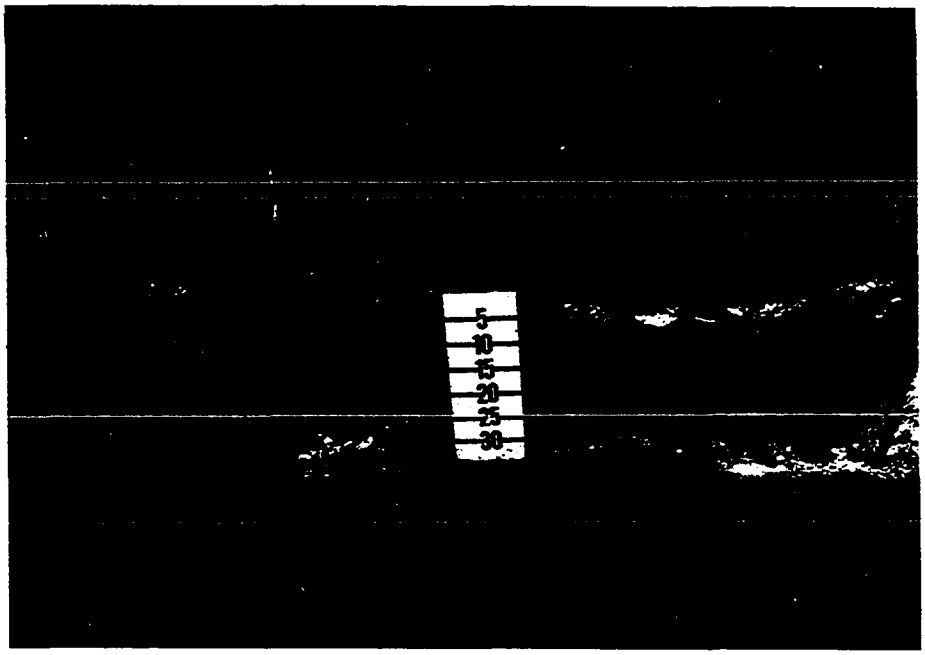
RESULTS AND DISCUSSION

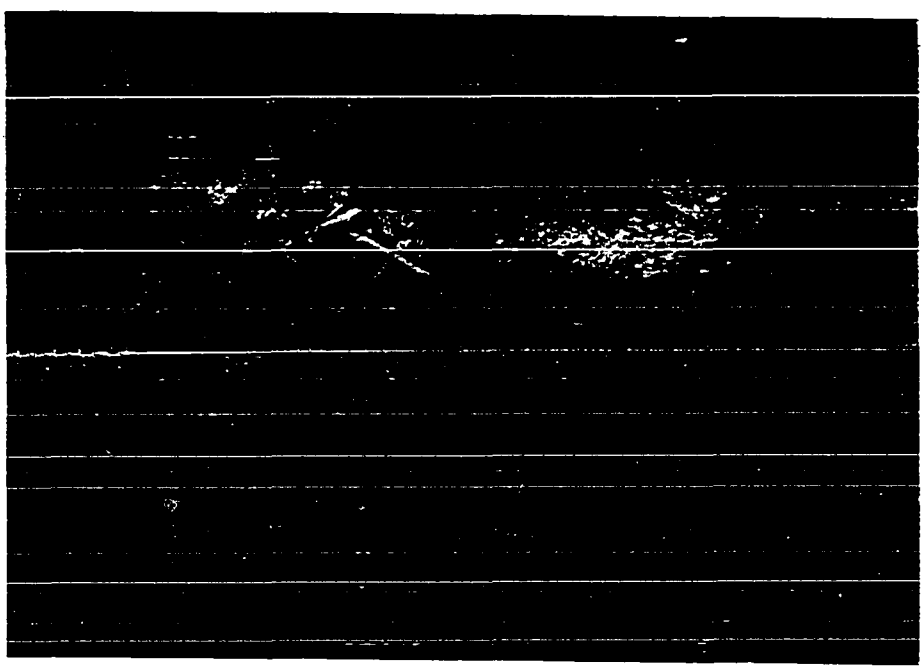
Study Areas I and II

The location and extent of acidity created by nitrification of NH_4^+ from injected NH_3 were clearly observable with the pH color indicator method at Areas I and II. Application of the organic pH indicator, bromocresol green, onto the whitened soil cross section produced a vivid color contrast of yellow color at lower pH values and blue color at higher pH values. Use of this qualitative field technique showed the presence of highly localized acidic zones. At both Area I (a ridge till-plant system) and Area II (a ridge slot-plant system), a single sharply delineated yellow-colored zone, representing an area of low pH, was detected between each corn row at all sampling sites at an average depth of 15 cm (Figure 2).

Shape and size of the observed acidic zones were variable, although the majority of the zones were roughly circular with a 12- to 15-cm diameter. McIntosh and Frederick (1958) reported that the injection of NH_3 into a soil created a cylindrically shaped distribution of NH_3 centered along the line of injection. With the application rate of 135 kg N/ha and 100-cm row spacing, these researchers detected an initial NH_3 zone that was 7.5 to 10 cm in diameter and, after maximum NH_3 diffusion, a zone that was 12.5 to 15 cm in diameter. Thus, the acidic zones observed in my study appeared to closely approximate typical circularly shaped NH_3-retention zones following the injection of NH_3. However, it was noted that a number of the zones were oblong with horizontal dimensions of 20- to 25-cm. It is reasoned that such horizontally elongated

Figure 2. The top photograph shows a representative site at Area II (ridge slot-plant system) in 1983. A distinct, highly localized acidic zone, yellow in color, is observed between each row. The bottom photograph shows a close-up of the acidic zone in the right interrow





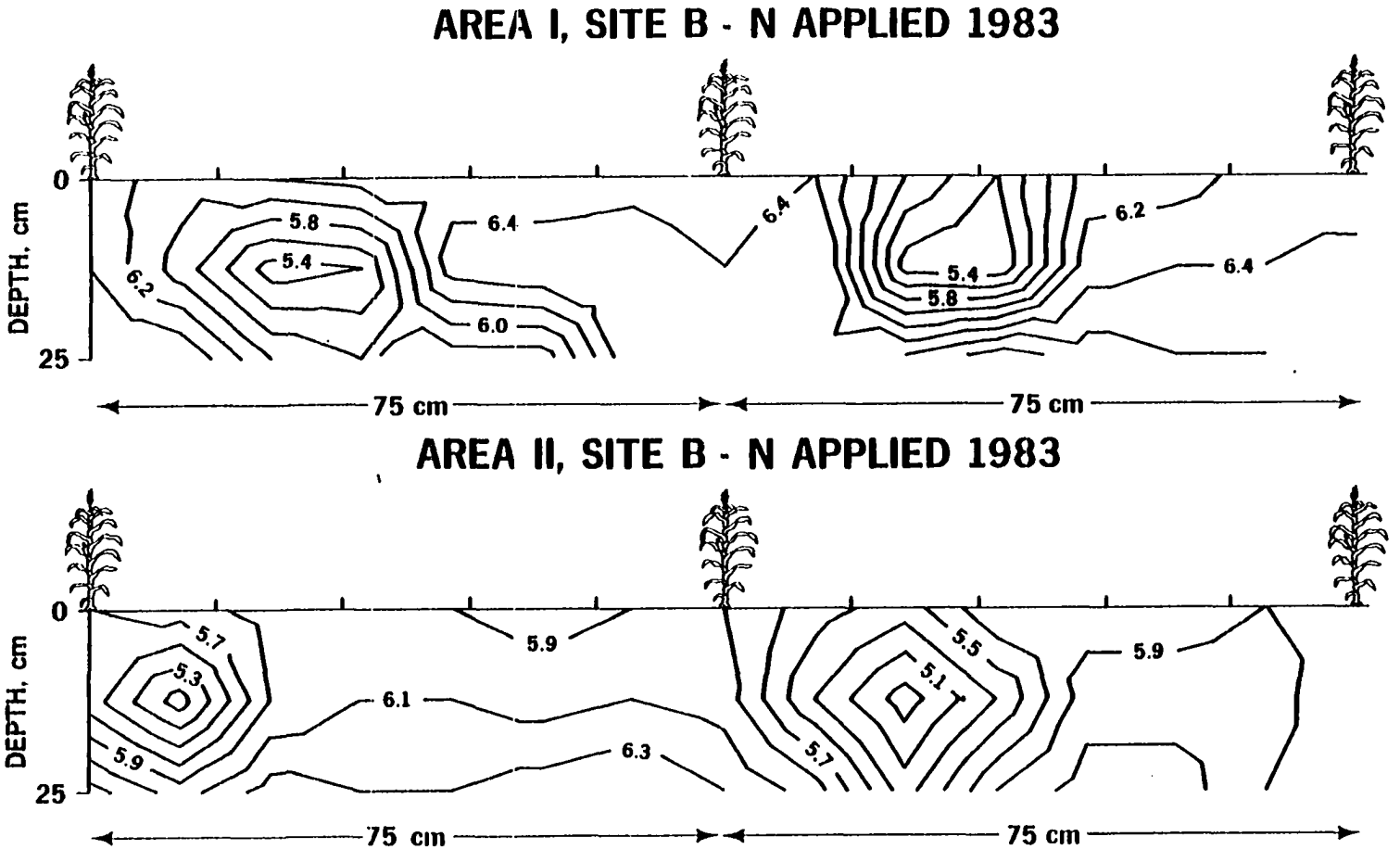
zone represents not only the current year's residual acidity but also acidity created by previous NH_3 applications. This supposition is based on evidence presented later in this paper that acidity from NH_3 fertilization shows little dissipiation over several years' time. Therefore, an apparent broadening or lateral spreading of the acidic zone would be expected with repeated NH_3 fertilizer injections applied at the same depth in close proximity.

A quantitative assessment of the acidifying effect of NH_3 showed significant decreases in soil pH in the interrows at all sites. Figure 3 shows representative soil pH distributions at Areas I and II in 1983. Soil pH within the acidic zones was 0.5 to 1.5 pH units lower than that of the surrounding bulk soil, with a mean difference of 0.9 pH units. The magnitude of decline in soil pH was not significantly different between Areas I and II.

At a small number of sites, the acidic zones were not confined to below the soil surface but extended to the surface, as noted in the right interrow of Site B, Area I (see Figure 3). This may be attributed to the formation of a narrow vertical channel left by the applicator blade under compacted or wet soil conditions. Ammonia would move rapidly upward through this opening and diffuse outward into the surrounding soil along this crevice to a point close to soil surface where it is closed by soil sealers (Papendick and Parr, 1966). Consequently, acidification from injected NH_3 may be detected at the soil surface.

Following a single application of NH_3 to soil, both McIntosh and Frederick (1958) and Nommik and Nilsson (1963) reported decreases in soil pH of 1.0 to 1.5 pH units in the NH_3-retention zone, as compared to the

Figure 3. Representative soil pH distributions at Area I and Area II following injection of NH_3 (180 kg N/ha, applied 6 May 1983, sampled 8 July 1983)


AREA I, SITE B - N APPLIED 1983
DEPTH, cm
0
25
5.8
5.4
6.2
6.4
6.0
6.4
6.2
5.4
5.8
6.4
75 cm
75 cm
AREA II, SITE B - N APPLIED 1983
DEPTH, cm
0
25
5.7
5.3
5.9
6.1
6.3
5.9
5.5
5.1
5.7
5.9
75 cm
75 cm

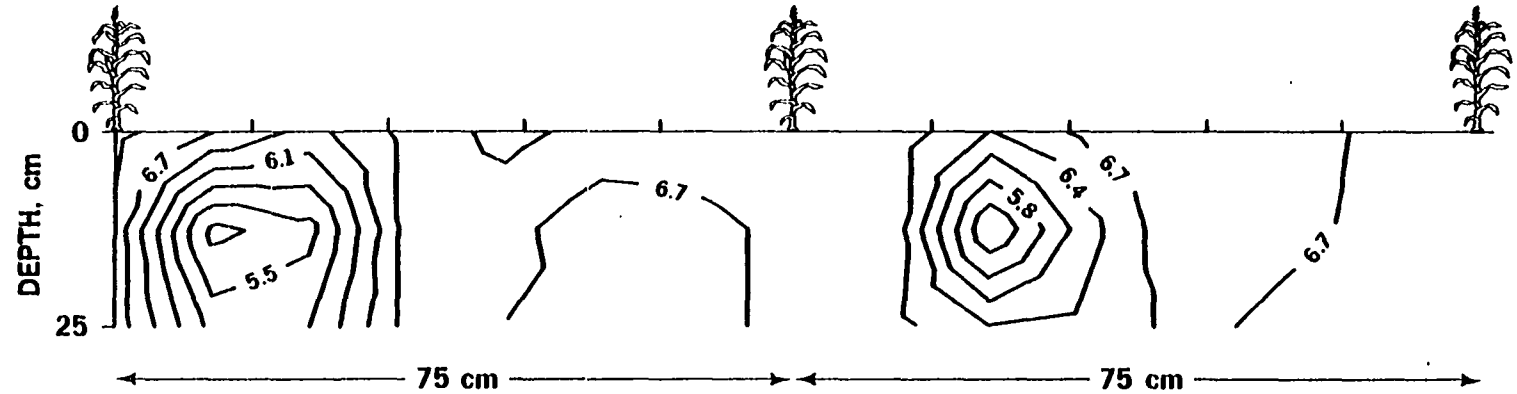
bulk soil after a 4-week period of rapid nitrification. At Areas I and II, where NH_3 applications were repeatedly injected in the same location, lower pH values might be expected than were observed in my study. However, NH_3 produces an alkaline reaction immediately after injection within its soil retention zone. Therefore, it is speculated that when NH_3 is injected directly into a residual acidic zone created by a prior injection, neutralization of a portion of the preexisting acidity will occur. Thus, the acidic zones are perpetuated, but the zones are not intensified to the degree that might be expected.

To determine persistence of the acidity observed at Areas I and II in 1983, Area II was selected for further study. In 1984, only one half of Area II received N fertilization. At sites which received no NH_3 application in 1984, the acidic zones were still clearly discernible in the field with the pH indicator method. Results of soil pH measurements show no or only slight (<0.3 pH units) dissipation in acidity over a one-year period (Figure 4). Soil pH within the residual acidic zones was 0.6 to 1.4 pH units lower than that of the surrounding bulk soil, with a mean pH difference of 0.8 units. The results of this study show that acidic zones resulting from injected NH_3 are highly persistent.

To complement my investigation on the acidifying effect of NH_3, in situ determinations with a flat-surface combination pH electrode were made at Area II in 1984. Figure 5 shows representative in situ pH distributions at sites with and without NH_3 fertilization. In viewing Figure 5, it should be noted that in situ values were, on the average, 0.8 pH units lower than laboratory determinations on 1:2 soil-water suspensions. At

Figure 4. Soil pH distribution at an Area II site in 1983 following injection of NH_3 (180 kg N/ha, applied 6 May, sampled 8 July) and in 1984 (no N applied in year of study, sampled 6 July)

AREA II, SITE F - N APPLIED 1983



AREA II, SITE F - NO N APPLIED 1984

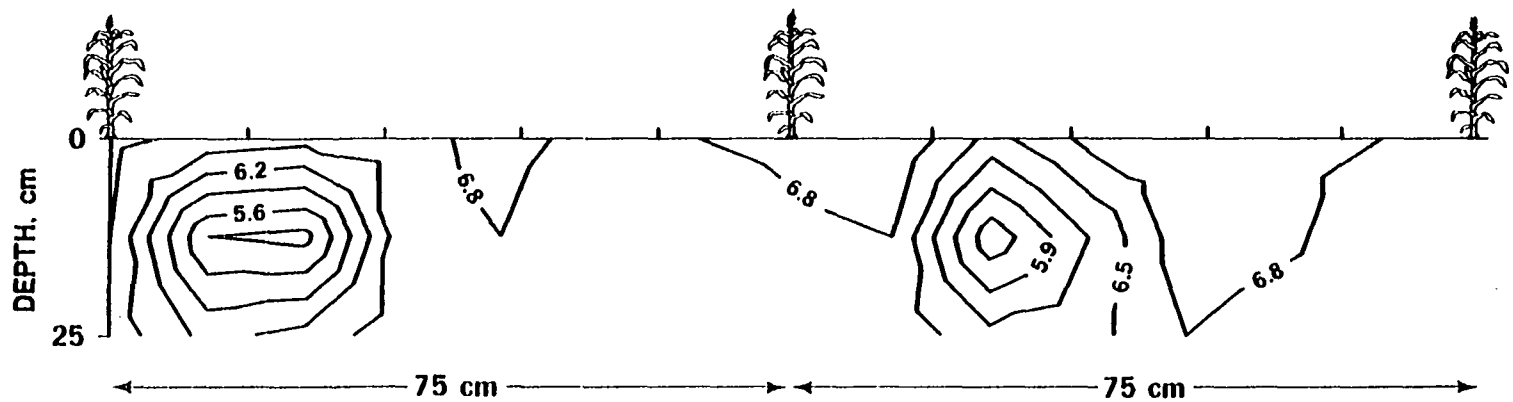
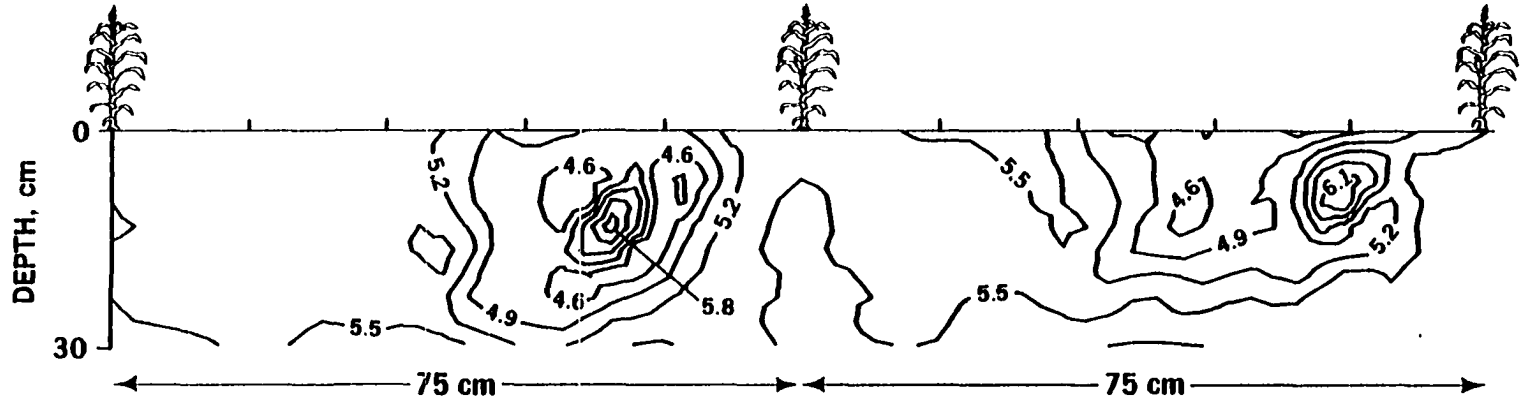
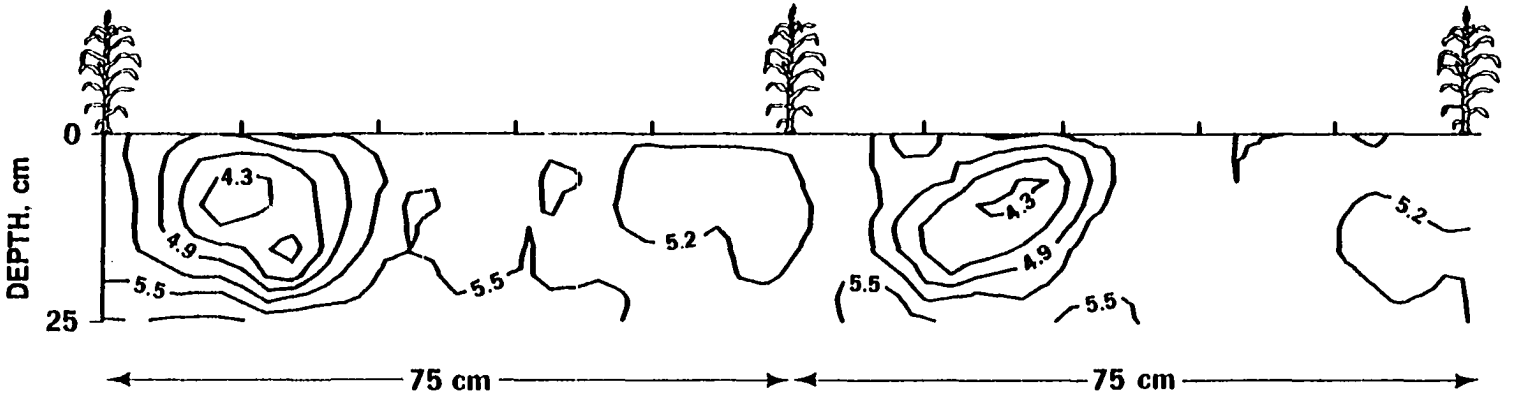


Figure 5. Representative soil pH distributions determined in situ at Area II with NH_3 fertilization (180 kg N/ha, applied 26 April 1984, sampled 11 July 1984 when nitrification not complete) and without NH_3 fertilization in the year of study (sampled 1 July 1984)

AREA II, SITE G - N APPLIED 1984



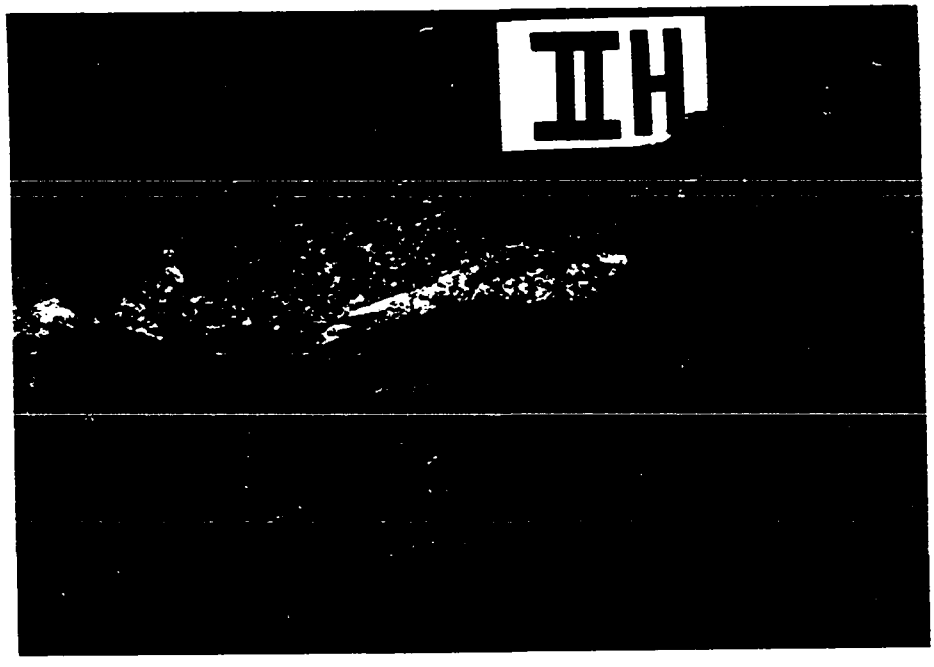
AREA II, SITE E - NO N APPLIED 1984



sites without N fertilization in the year of study, in situ soil pH of the residual acidic zones was 0.5 to 1.2 units lower than that of the surrounding bulk soil, with an average difference of 0.8 pH units. The observed difference of 0.8 pH units obtained in this in situ study was consistent with my other results evaluating the persistence of acidity. At sites with N fertilization in the year of study, results of in situ pH measurements showed that nitrification had not yet occurred throughout the NH_3-retention zone at the time of sampling. Significantly higher pH values were still detected at the center of the zone 2.5 months after the injection of NH_3. This finding was in agreement with field observations, which indicated the presence of a small 4-cm diameter blue-colored zone situated within a 16- to 24-cm diameter yellow-colored zone between each corn row (Figure 6). Soil pH within the non-nitrified zone was, on the average, 1.4 units higher than that within the nitrified acidic zones. Soil pH within the acidified zones was 0.6 to 1.3 units lower than the pH of the surrounding bulk soil, with a mean difference of 0.8 pH units.

To assess the reliability of field pH measurements, in situ pH readings made at the three fertilized sites were compared to laboratory determinations made on 1.8-cm diameter core soil samples collected at each point of in situ measurement. General relationships are summarized in Figure 7. A strong linear relationship ($r = 0.99$) was observed between pH values obtained with the flat-surface combination pH electrode on saturated pastes and pH values determined with commonly used bulb-type glass and calomel reference electrodes on 1:1 water-soil suspensions (a standard method of pH measurement, Peech, 1965). The finding agrees with

Figure 6. The top photograph shows an NH_3 injection zone at Area II (ridge slot-plant system) in 1984. The zone consists of a dark blue center (a non-nitrified zone) surrounded by a distinct yellow ring (a nitrified zone). To the left of this zone, a residual yellow acidic zone, created by a previous years' NH_3 application, is also detected. The bottom photograph shows a close-up of the current year's NH_3 zone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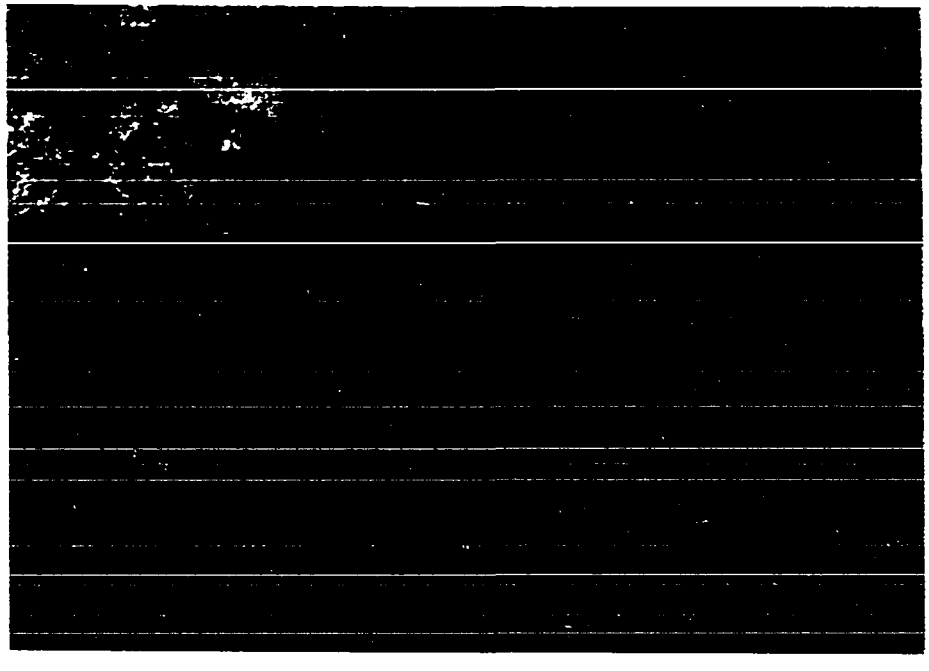
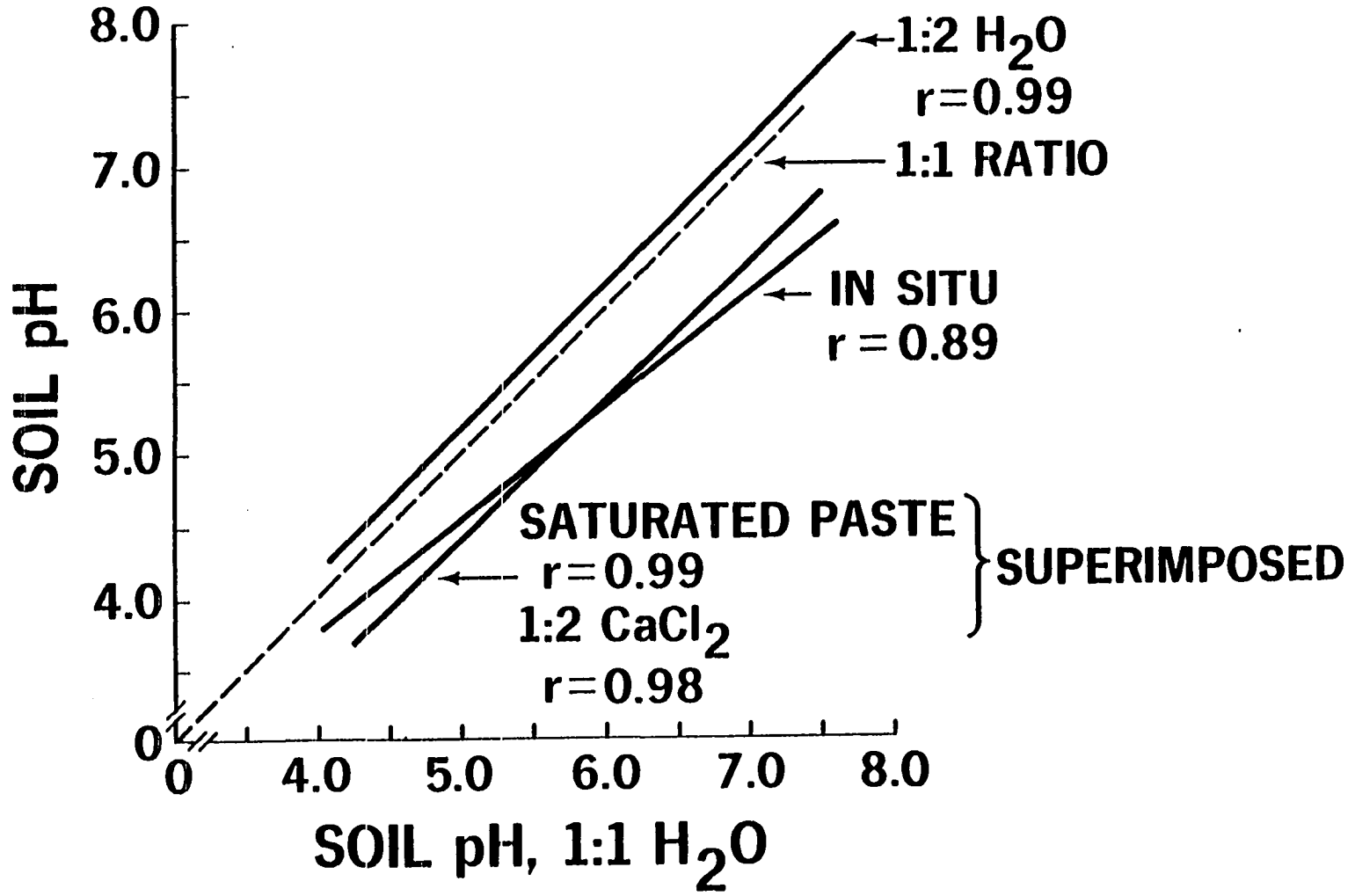


Figure 7. Relationship between soil pH determined on 1:1 soil-H_2O suspensions and soil pH determined by four methods: in situ and on saturated pastes of core samples with a flat-surface combination electrode, and on 1:2 soil-H_2O suspensions and 1:2 soil-0.01M $CaCl_2$ suspensions with bulb-type glass and calomel reference electrodes


8.0
7.0
6.0
5.0
4.0
0
SOIL pH
1:2 H_2O
r=0.99
1:1 RATIO
IN SITU
r=0.89
SATURATED PASTE
r=0.99
1:2 $CaCl_2$
r=0.98
SUPERIMPOSED
0
4.0
5.0
6.0
7.0
8.0
SOIL pH, 1:1 H_2O

the work of Breitenbeck and Bremner (1984) showing that laboratory determinations made with the Sensorex flat-surface combination pH electrode were highly correlated ($r > 0.98$) with pH values determined by suspension methods. As shown by the data of Figure 7, however, the correlation coefficient between soil pH values obtained with the Sensorex electrode in situ and values determined by the conventional 1:1 soil-H_2O suspension method was lower ($r = 0.89$) than the coefficients between pH values obtained by the laboratory methods. The lower correlation observed between field and laboratory measurements may be attributed to uncontrolled environmental factors such as partial pressure of CO_2, soil temperature, and soil water content, each of which may be highly variable under field conditions and have an effect on soil pH readings. Another contributing factor is that an in situ measurement represents the pH only at a specific point of electrode contact on the soil surface, but a laboratory measurement represents the average soil pH of a 25-g core sample. Although in situ soil pH evaluation has inherent limitations, use of the Sensorex flat-surface combination pH electrode provided a reasonable estimate of soil pH under field conditions.

In summary, field and laboratory data obtained from the investigation on the acidifying effects of NH_3 at Areas I and II indicate that a distinct highly localized persistent acidic soil zone was created by repeated application of NH_3 in the interrow of the ridge systems studied. Soil pH of the acidic zones was significantly lower than the pH of the surrounding bulk soil by 0.9 pH units. It is interesting to note that root proliferation was clearly observable within these acidic zones,

which had mean pH values of 5.1 to 5.8. This observation suggests that root growth was not severely inhibited by this level of acidity. The data indicate that only a limited portion of the soil was acidified by long-term NH_3 application. Considering a 75-cm row width and a 25-cm sampling depth, acidification was confined to approximately 15% of the exposed surface area, with a range of 5 to 25%. It is apparent that NH_3 had been injected close to the same vicinity each year in these ridge systems where crop rows were located in nearly the same location every year. Based on the extent and degree of acidity observed in these studies, it is concluded that a yield-limiting problem due to acidification by continuous NH_3 applications is not likely in ridge till-plant and ridge slot-plant systems.

Study Areas III and IV

The size, shape, and distribution of acidic zones resulting from injected NH_3 were observable at Areas III and IV with the pH color indicator method. The organic pH indicator, chlorophenol red, effectively produced a sharp color contrast of yellow color at lower pH values and pink color at higher pH values. Color patterns observed at Areas III and IV (flat no-till systems) were more variable and complex than those observed at Areas I and II (ridge systems).

At Area III planted to corn, a localized 14- to 18-cm circular zone of intense yellow color was detected in the center of each interrow at an approximate 12-cm depth. This acidic zone corresponded to the location of the current year's side-dressed NH_3 application. In addition, a

varying number of yellow-colored zones were observed between each corn row at an approximate 20-cm depth (Figure 8). These acidic zones represented the location of previous years' more deeply applied preplant NH_3 applications. Acidic zones at a 20-cm depth were also observed at Area IV, which was planted to a sorghum-sudan hybrid without N fertilization. These residual acidic zones were created by NH_3 applications prior to the year of study when in corn and were scattered throughout the profile. As in Area III, the length of time these individual acidic zones had existed could not be established. The field observations and accompanying interpretations noted for Areas III and IV were consistent with the management practices indicated by the farm operator.

Soil pH distribution patterns determined by soil analysis reflected the color patterns observed in the field. Figure 9 shows representative pH distributions at Areas III and IV. The data for the Area III site (Figure 9) indicate at the center of each interrow the presence of a highly acidified area that is thought to be the combination of a current year's acidic zone and a previous year's more deeply located acidic zone. Soil pH within these acidic zones was 1.1 to 1.6 units lower than that of the surrounding soil, with an average difference of 1.4 pH units. The data in Figure 9 shows, directly below each corn row at the Area III site, additional residual zones whose dates of origin are unknown. Soil pH distribution at the Area IV site (Figure 9) indicates the presence of four separate residual acidic zones. It is speculated that the two zones of greater intensity (minimum pH values 5.2), located one row width apart, originated from NH_3 injected one year earlier. The findings at Area IV

Figure 8. The photograph shows a representative site at Area III (flat no-till system). Numerous acidic zones, yellow in color, are observed throughout the soil profile

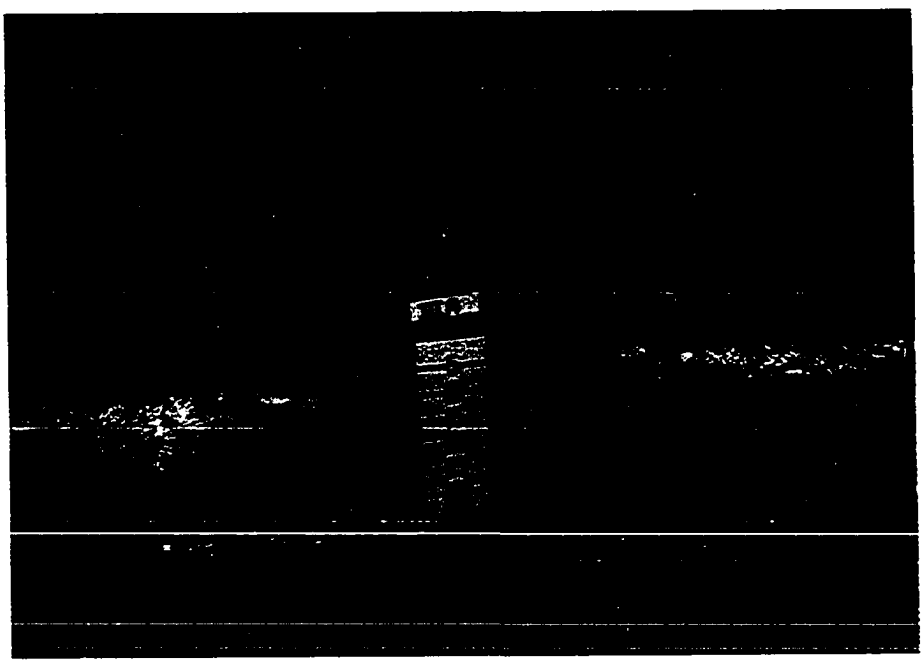
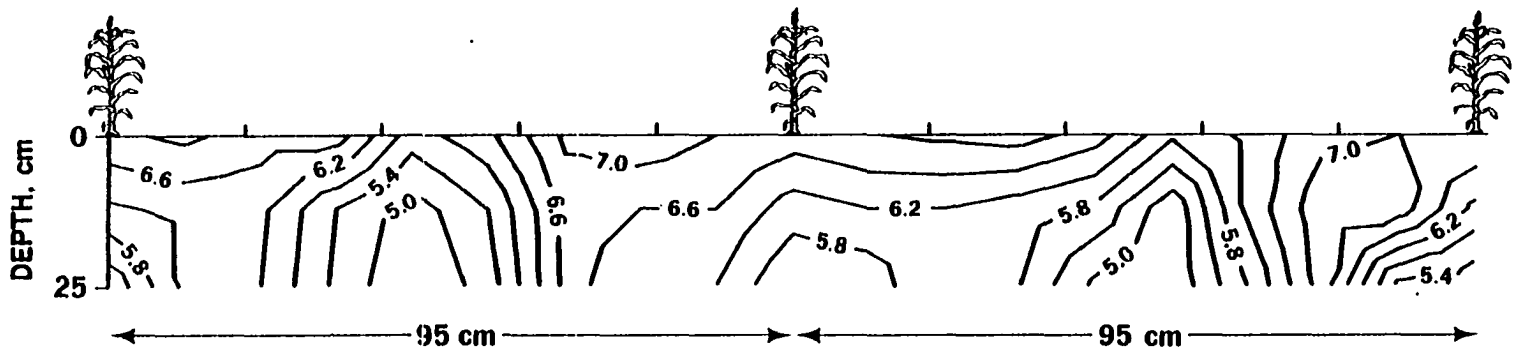
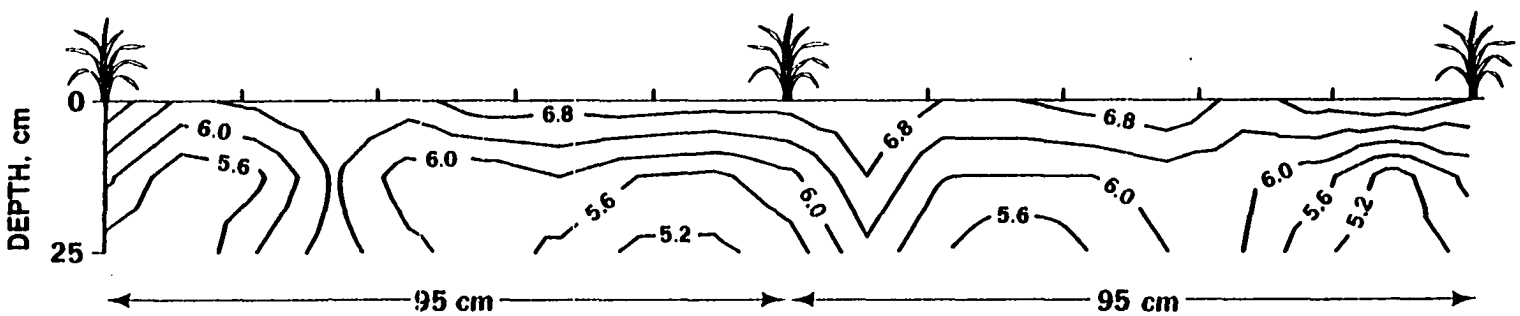


Figure 9. Representative soil pH distributions at Area III following injection of NH_3 (225 kg N/ha, applied 10 June 1983, sampled 3 August 1983) and at Area IV (no N applied in year of study, sampled 3 August 1983)

AREA III, SITE E - N APPLIED 1983



AREA IV, SITE A - NO N APPLIED 1983



clearly support the results from our studies at Area II showing that acidity arising from NH_3 applications is highly persistent.

In summary, results of the study at Areas III and IV indicate that continuous application of NH_3 creates numerous persistent acidic zones that are scattered throughout the interrow in the flat no-till system. It is apparent that NH_3 had not always been injected in the same vicinity each year. Thus, a greater extent of the soil was acidified in the flat no-till system compared to the ridge systems studied. Considering a 95-cm row width and a 25-cm sampling depth, generally 25% or more of the exposed surface area was affected by long-term application of NH_3. Soil pH of the current year's acidic residual zones was significantly lower than the bulk soil pH by 1.4 pH units. Prolific root growth within these acidic zones, as was observed at Areas I and II, was not noted in the field. The low pH values of 4.6 to 5.2 may have inhibited root growth within these zones.

Because of the size and persistence of an acidic zone created by a single NH_3 injection, extensive acidification throughout the lower soil profile could occur possibly as a result of repeated NH_3 injections. If acidification by NH_3 occurred, amelioration of such acidity might be difficult. Blevins et al. (1978) reported that unincorporated lime was highly efficient in neutralizing surface acidification from broadcast N applications in no-till systems. Yet, it seems unlikely that deeper subsurface acidification created by injected NH_3 fertilizer would be as readily counteracted by surface liming. Thomas (1975) and Blevins et al. (1978) indicated that the higher soil organic matter levels at the

surface of no-till soils reduced exchangeable Al levels and, thereby, alleviated the adverse effects of low soil pH arising from surface N applications. However, at deeper depths where organic matter levels are markedly lower, it is expected that the detrimental effects of subsurface acidification would not be abated. It is concluded that yield-limiting problems due to acidification by long-term NH_3 usage potentially could develop in no-till systems. It should be recognized, however, that the total volume of soil affected by acidity in flat no-till systems would vary greatly according to individual farm operator practices. Efforts toward localized placement of N by the operator could effectively minimize potential problems due to the acidifying effects of continuous NH_3 application in conservation tillage systems.

Study Areas V and VI

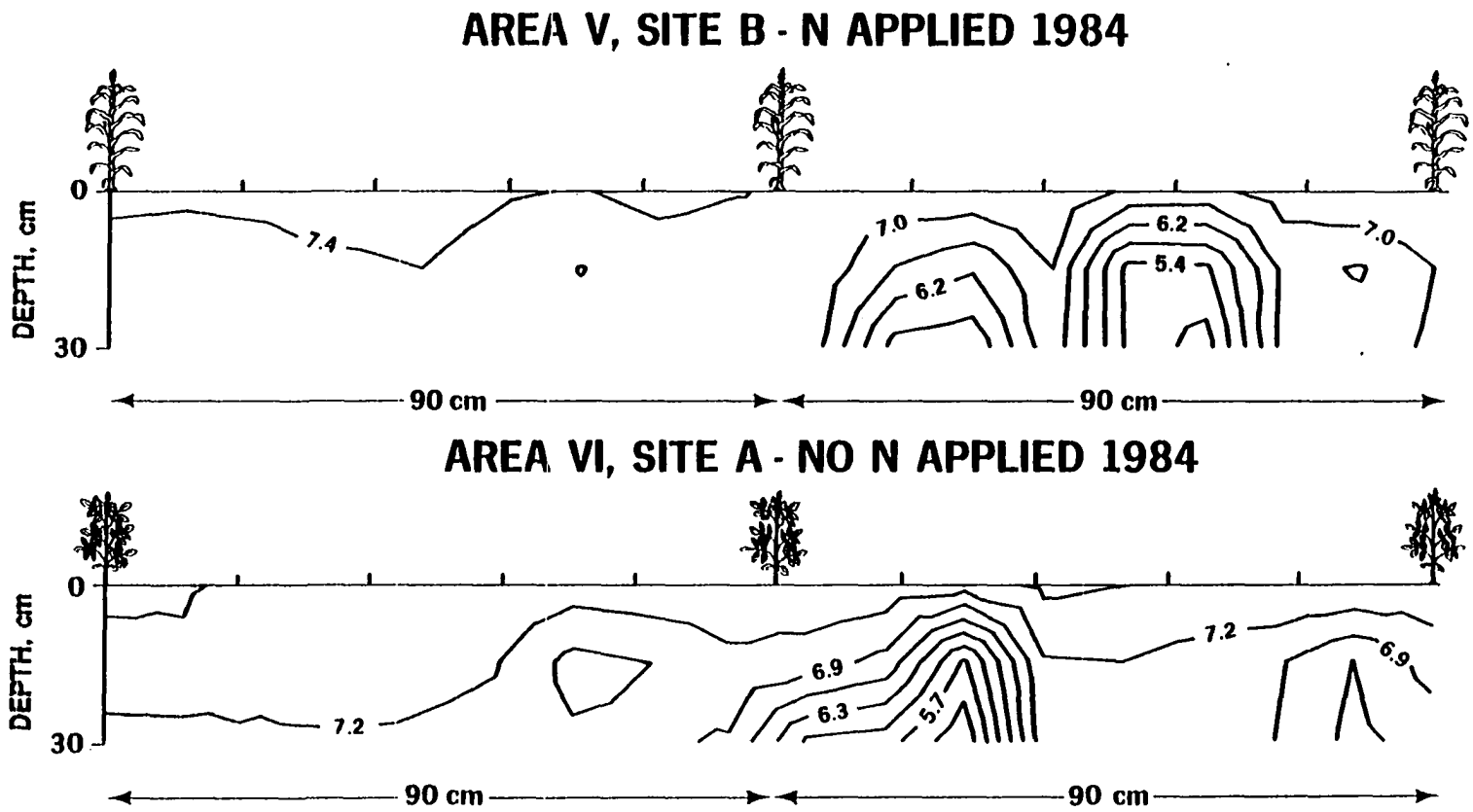
In a ridge till-plant system similar to Area I, Areas V and VI represented a unique field situation because NH_3 had been injected in alternate interrows and, as such, it was possible to study not only locations with high N application rates, but also closely adjacent locations with no history of NH_3 application. The extent and distribution of acidity at Areas V and VI were readily detected with the pH indicator field technique. The organic pH indicator, bromocresol green, provided a vivid color contrast between areas of lower pH, yellow in color, and areas of higher pH, blue in color.

In the injected interrows at Area V, the current year's NH_3 application to corn at the 20-cm depth appeared as a circular 7-cm blue-

colored zone surrounded by a distinctly yellow-colored 4-cm wide ring. With nitrification incomplete approximately 1.5 months following the injection of a high concentration of NH_3, soil pH within the non-nitrified center zone was 1.7 to 2.5 pH units higher than that in the peripheral acidic ring. Soil pH in the peripheral nitrified ring was 1.2 to 2.0 pH units lower than the surrounding bulk soil pH, with a mean difference of 1.6 pH units. Directly next to the current year's NH_3 zone, a single 10-cm yellow-colored zone was also detected. This residual acidic zone represented the location of a prior NH_3 injection made possibly two or four years earlier when in corn. No acidic zones were noted in the alternate interrows that had received no NH_3. The mean soil pH for the alternate interrows without N fertilization was 0.5 pH units higher than that for the interrows with repeated NH_3 applications.

Figure 10 shows a representative pH distribution pattern at Area V. The data indicate the presence of two acidic zones in the right interrow. The left zone is a residual acidic zone created prior to the year of study. The right zone is the current year's NH_3 injection zone. It should be noted that because of the block soil sampling technique employed, the pH contour lines depicting that zone do not clearly differentiate nitrified and non-nitrified regions of the NH_3 zone. In the left interrow, no marked acidity was observed. This finding was expected since no NH_3 had been applied in the alternate interrows of Area V in the previous 12 years.

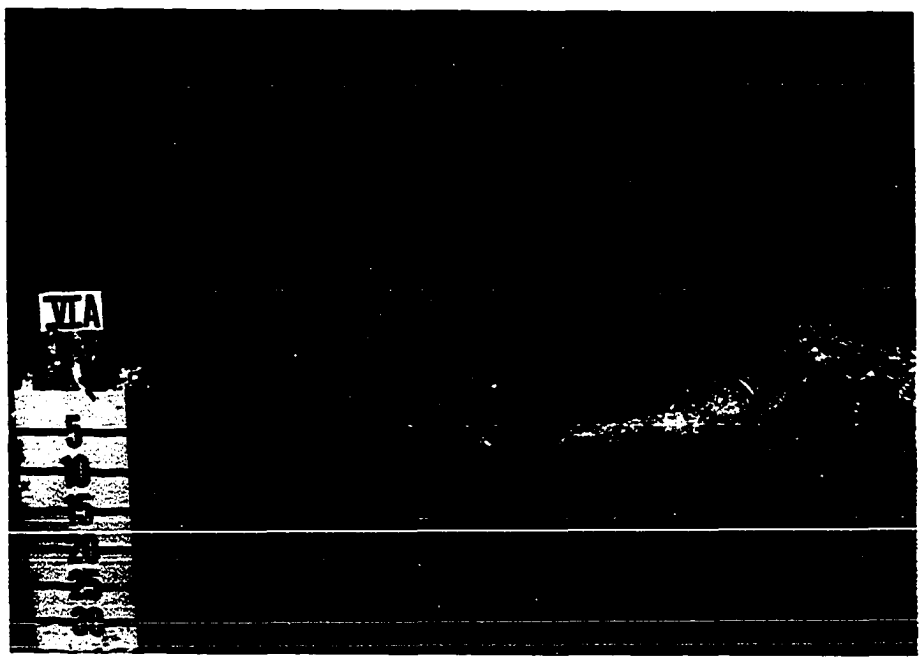
Figure 10. Representative soil pH distributions at Area V following injection of NH_3 (145 kg N/ha, applied 12 June 1984, sampled 24 July 1984) and at Area VI (no N applied in year of study, sampled 24 July 1984)


AREA V, SITE B - N APPLIED 1984
DEPTH, cm
0
30
7.4
7.0
6.2
5.4
6.2
7.0
90 cm
90 cm
AREA VI, SITE A - NO N APPLIED 1984
DEPTH, cm
0
30
7.2
6.9
6.3
5.7
7.2
6.9
90 cm
90 cm

At Area VI planted to soybeans, a prominent 13-cm yellow-colored zone was observed at a 25-cm depth in each of the interrows with a history of NH_3 application. This residual acidic zone corresponded to the location of the previous year's NH_3 injection when in corn. Soil pH within the acidic zone was 1.0 to 1.8 pH units lower than the pH of the surrounding soil. Adjacent to this zone, a less pronounced 10-cm yellow-colored acidic zone was also detected in the interrow (Figure 11). This residual zone represented the location of the NH_3 injection made three years earlier when in corn. Soil pH within the acidic zone was 0.9 to 1.5 pH units lower than the bulk soil pH. From these findings, it is apparent that acidic zones created by NH_3 injection are highly persistent. A typical soil pH distribution pattern at Area VI (Figure 10) shows in the right interrow a large acidic zone that represents the combination of two residual acidic zones. Because two NH_3 applications had been injected in close proximity to one another, the corresponding acidic zones appear as a single elongated zone in this figure. In the adjacent interrow that received no N fertilization, no marked acidity is evident.

In summary, results of the study on the acidifying effects of NH_3 at Areas V and VI indicate that distinct highly persistent acidic zones were created in the alternate interrows, which had received repeated NH_3 applications. Soil pH of the acidified zones was generally 1.0 to 1.8 pH units lower than the surrounding bulk soil pH. It is interesting to note that prolific root growth was observed in these acidic zones with pH values of 5.0 to 5.7. This field observation suggests that root growth was not greatly inhibited by this degree of acidity. No

Figure 11. The photograph shows a representative site at Area VI (ridge till-plant system). A prominent acidic zone, yellow in color, is observed in the center of the interrow. Situated to the left of this zone, a less pronounced acidic zone is also detected


VIA

pronounced acidity was detected in the adjacent interrows without NH_3 fertilization. The data indicate that only a limited portion of the soil was acidified by continuous NH_3 applications in this type of management system. Considering a 30-cm sampling depth and a 180-cm width (equal to two 90-cm row widths), acidification was confined to approximately 10% of the exposed surface area, with a range of 7 to 13%. Based on the extent and degree of acidity observed at Areas V and VI, it is concluded that a yield-limiting problem due to acidification by long-term NH_3 application is not likely in ridge systems with similar N placement practices.

SUMMARY

Subsurface soil acidity resulting from repeated NH_3 applications in long-term conservation tillage systems that do not disturb the NH_3 injection zone was studied by: (1) observation of the size, shape, and distribution of acidic zones in the field using a pH color indicator method and (2) intensive quantitative sampling of the upper 25- to 30-cm soil layer with subsequent laboratory analysis for soil pH. Acidic soil zones created by the nitrification of the injected NH_3 were roughly circular in shape with 12- to 18-cm diameters. Soil pH of the acidic zones was generally 0.9 to 1.8 pH units lower than that of the surrounding bulk soil. In the ridge till-plant and ridge slot-plant systems studied, a distinct highly localized persistent acidic soil zone was detected in each interrow. Based on the extent and degree of acidity observed, it is concluded that yield-limiting problems due to acidification by continuous NH_3 applications is not likely in ridge management systems. In the flat no-till systems studied, numerous persistent acidic soil zones were observed scattered throughout each interrow. It is concluded that soil acidity problems due to long-term NH_3 usage potentially could develop in no-till systems where NH_3 is not injected in the same vicinity each year. Efforts toward localized placement of N by the farmer operator could effectively minimize potential problems due to the acidifying effects of NH_3 in conservation tillage systems.

PART II. STRATIFICATION OF PHOSPHORUS AND POTASSIUM IN CONSERVATION TILLAGE SYSTEMS

INTRODUCTION

Conservation tillage methods are increasingly being used by crop producers throughout the United States. By 1984, over 40 million crop ha were under some form of conservation tillage management in the United States (Conservation Tillage Information Center, 1985). The adoption of such practices by farmers has created pronounced changes in the physical, chemical, and biological properties of soils. Blevins et al. (1983), among others, have shown that soil nutrient distributions may be altered markedly by the type of tillage employed. Such changes in nutrient distribution patterns may have a significant effect on nutrient availability and crop yield.

In conventional tillage systems, the upper 15- to 20-cm of soil is thoroughly mixed, whereas in conservation tillage systems minimal disturbance of soil occurs. The resultant effect is a surface accumulation of phosphorus (P) and potassium (K) where P and K fertilizer has been broadcast-applied in conservation tillage systems. Without mechanical incorporation of the fertilizer, these relatively immobile nutrients remain concentrated in the upper approximate 5 cm of soil (Shear and Moschler, 1969; Triplett and Van Doren, 1969; Fink and Wesley, 1974; Ketcheson, 1980; Cruse et al., 1983). This finding has created concern that the build-up of P and K at the soil surface may create plant nutritional problems.

Most investigations to determine levels of soil P and K in conservation tillage systems have utilized sampling methods in which core samples are collected with a soil probe at designated surface points

across a field and the core samples are then subdivided to represent various depth increments. No research work has been conducted to assess definitively the spatial distribution of P and K in soil profiles under conservation tillage management. This information is essential to understanding potential factors affecting nutrient availability in no-plow systems.

I report here the results of an intensive sampling program to determine vertical and horizontal P and K distributions in conservation tillage systems with long-term histories of broadcast P and K fertilizer applications.

MATERIALS AND METHODS

Three field locations, each representing a different crop-fertilizer-tillage system, were investigated in July-August 1983. Each area has a long-term history of surface-applied P and K fertilization in a conservation tillage system. Areas I and II are located at the Agronomy and Agricultural Engineering Research Center near Ames, IA. For nine consecutive years, Area I has been in a ridge till-plant system and Area II has been in a ridge slot-plant system. A corn-soybean rotation was followed the first five years, and corn has been grown each subsequent year. The soil at both areas is a Webster clay loam (Typic Haplaquoll). Fertilizer P (30 kg P/ha as 0-46-0) and K (60 kg K/ha as 0-0-60) were broadcast applied in the fall of 1982 at Areas I and II. Similar rates of P and K were surface-applied at these areas in the preceding eight years. Areas I and II were planted to corn in May 1983 and, because of an extended period of wet soil conditions, were not later cultivated in 1983 to rebuild existing ridges. Area III is located at the Frederick farm near Springdale, IA. At this location, continuous corn under a flat no-till system has been grown on a Tama silt loam (Typic Argiudoll) for the last 10 years. Planted to corn April 1983, Area III received a starter fertilizer application (80 kg/ha of a 5-10-22 grade) and a broadcast application of P (30 kg P/ha) and K (75 kg K/ha). This area was fertilized at similar P and K rates in the preceding nine years. A once-through cultivation for weeds to an approximate 5-cm depth was performed. Chemical and physical properties of soils in the areas studied are shown in Table 2.

Six sites were examined at each of the three field locations. At each site, a trench, extending across a distance of three adjacent crop rows (two interrows), was excavated to expose a vertical section of soil from the soil surface to a 25-cm depth. Each trench was then quantitatively sampled by 10-cm horizontal increments and 0- to 5-cm, 5- to 15-cm, and 15- to 25-cm vertical increments.

Available P was determined colorimetrically after extraction with the Bray-1 solution and subsequent addition of the Fiske-Subbarrow reducing agent, 1-amino-2 napthol-4 sulfonic acid (Knudsen, 1980). Available K was measured by flame photometry after extraction with ammonium acetate (Pratt, 1965).

Contour lines for soil P and K were obtained by using the CONTR 2 program that is available at the Iowa State University Computation Center.

Table 2. Chemical and physical properties of soils in areas studied

Depth	CEC[c]	Organic C[d]	Particle size distribution (mm)[a] Sand (2-0.05)	Silt (0.05-0.002)	Clay (<0.002)	Gravimetric water content[b] At -0.03 MPa	At -1.5 MPa
-cm-	cmol(+)kg^{-1}				%-		
			Area I				
0-5	48	3.9	26	46	28	28	21
5-15	49	3.6	27	45	28	29	22
15-25	53	3.1	25	45	30	30	24
			Area II				
0-5	39	3.4	37	40	23	25	18
5-15	41	3.0	33	43	24	26	19
15-25	42	2.5	30	43	27	27	20
			Area III				
0-5	31	2.1	3	73	24	27	18
5-15	31	1.8	2	73	25	26	18
15-25	34	1.2	3	67	30	28	20
			Area IV				
0-5	30	2.6	3	74	23	29	19
5-15	28	1.7	3	71	26	27	18
15-25	29	1.1	2	68	30	29	19

[a]Particle size analysis by pipette method (Walter et al., 1978).

[b]Water content by pressure plate extractor (Soil Survey Staff, 1984; Richards, 1965).

[c]CEC by ammonium saturation method (Chapman, 1965).

[d]Organic C by Walkley-Black method (Allison, 1965).

RESULTS AND DISCUSSION

Results of this study show that pronounced vertical stratification of P and K occurred in the ridge till-plant (Area I), ridge no-till (Area II), and flat no-till (Area III) systems (Table 3). Significant surface accumulations of P and K were observed in the upper 5-cm layer of soil. Surface values for available P and K were, on the average, 3.5 times greater than those for the 5- to 15-cm soil layer. This can be attributed to (1) non-incorporation of surface-applied P and K over a 8- to 10-year period and (2) maintenance of a high level of surface crop residue that decomposes at the soil surface. In contrast to the stratified conditions observed at these tillage systems, relatively uniform P and K distributions in the upper 15-cm of soil have been reported for conventional tillage systems (Triplett and Van Doran, 1969; Fink and Wesley, 1974; Cruse et al., 1983).

The effect of broadcast fertilizer applications on soil P and K in conservation tillage systems is further illustrated in Figures 12 and 13 that show representative spatial distribution patterns of available P and K, respectively, at selected sites in Areas I, II, and III. Soil nutrient profiles showed marked stratification of P and K in three tillage systems studied. Furthermore, row-interrow differences in soil P and K were apparent in Areas I and II. Localized high concentrations of P and K were frequently observed in the interrows of these ridge systems. This general pattern of interrow nutrient accumulation was not detected in the flat no-till system. Shallow pockets of higher P

Figure 12. Representative soil P distributions at Area I (ridge till-plant system), Area II (ridge slot-plant system), and Area III (flat no-till system). Available P is expressed as mg kg^{-1}

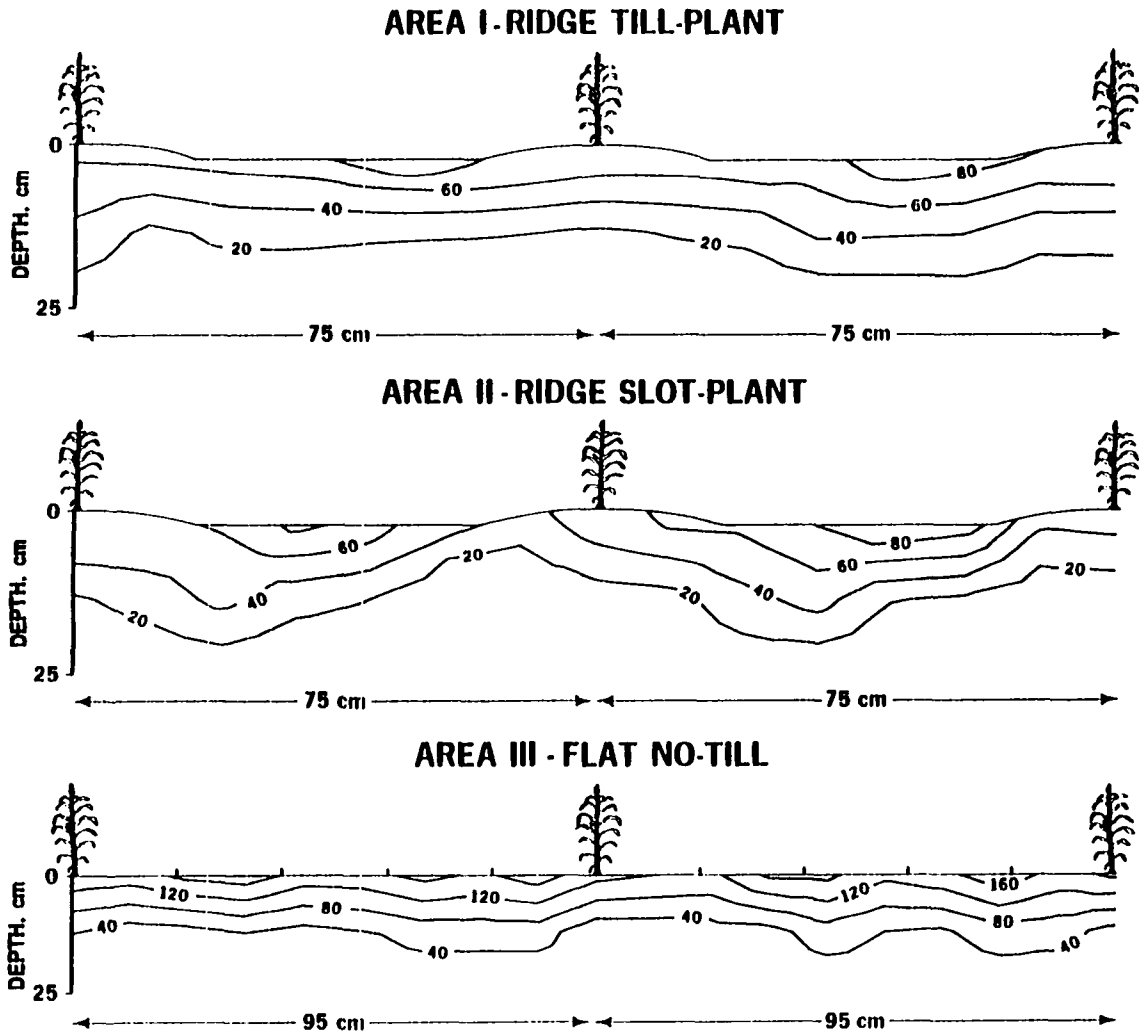

AREA I - RIDGE TILL-PLANT
DEPTH, cm
0
25
80
60
40
20
75 cm
75 cm
AREA II - RIDGE SLOT-PLANT
DEPTH, cm
0
25
80
60
40
20
75 cm
75 cm
AREA III - FLAT NO-TILL
DEPTH, cm
0
25
160
120
80
40
95 cm
95 cm

Figure 13. Representative soil K distributions at Area I (ridge till-plant system), Area II (ridge slot-plant system), and Area III (flat no-till system). Available K is expressed as mg kg^{-1}

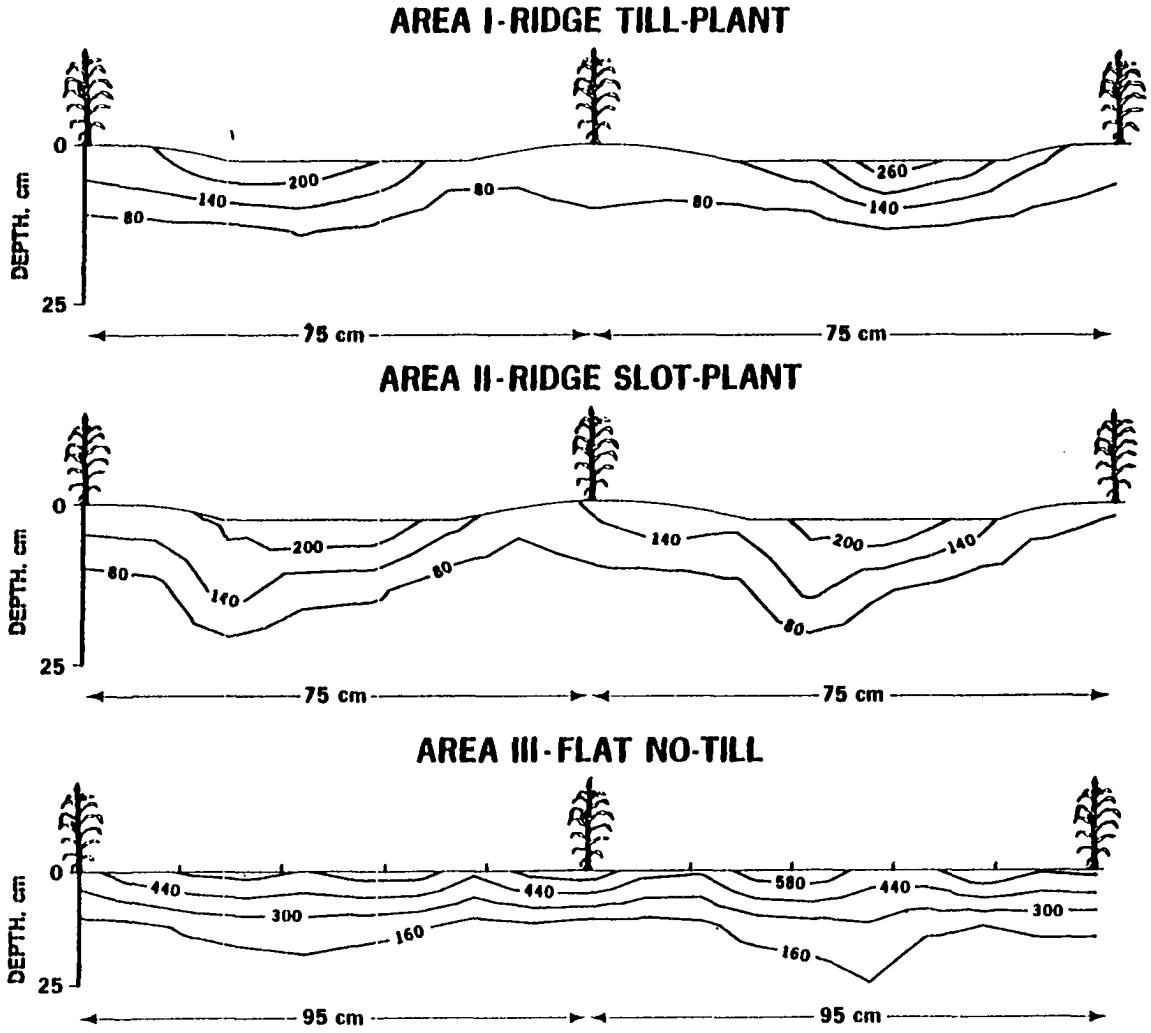

AREA I-RIDGE TILL-PLANT
DEPTH, cm
0
25
200
140
80
80
80
260
140
75 cm
75 cm
AREA II-RIDGE SLOT-PLANT
DEPTH, cm
0
25
200
80
140
80
140
200
140
80
75 cm
75 cm
AREA III-FLAT NO-TILL
DEPTH, cm
0
25
440
300
160
440
160
580
440
300
95 cm
95 cm

Table 3. Available P and K distributions with depth at Area I (ridge till-plant system), Area II (ridge slot-plant system), and Area III (flat no-till system)

Depth	Area I		Area II		Area III	
	P	K	P	K	P	K
-cm-	---------- mg kg^{-1} ----------					
0-5	92	194	69	176	129	523
5-15	43	51	17	48	35	172
15-25	13	26	4	25	7	50

and K concentrations were distributed irregularly across the soil surface in this tillage system.

The observed differences in nutrient distribution patterns may be related to several factors. It is expected that ridges that are permanently established at specific row-width intervals, as at Areas I and II, significantly affect P and K distributions and contribute to nutrient accumulation in the interrow. In ridge systems, surface crop residues tend to collect in the interrow. As these plant materials are leached and decomposed, nutrients are released and accumulate in this vicinity. Interrow nutrient accumulation also may be caused by localized erosion of fall-applied P and K fertilizer from the ridge to the interrow region. Because ridging entails the movement of soil, a ridging operation in itself may influence nutrient distribution. However, its effect on P and K distribution patterns would be highly variable depending on farm operators' equipment and related field practices that would

determine the location and extent of soil moved. Disc-hillers used to rebuild ridges at Areas I and II primarily moved soil from the base of the old ridges to the row and, therefore, left a relatively undisturbed interrow zone of accumulated P and K.

Another potential factor contributing to the apparent interrow nutrient accumulation, as observed at Areas I and II, is nutrient uptake by the crop. In long-term ridge systems where planting is done in the same approximate location each year, nutrient depletion as a result of crop uptake may occur in the row, relative to the interrow. In addition, soil compaction in established wheel-traffic lanes may greatly reduce root exploration and, thus, nutrient uptake in compacted interrow zones.

The effect of P and K distribution patterns, similar to those observed in my study, on plant growth has not been established. Investigations on P and K uptake from surface-applied fertilizer in conservation tillage systems have been conducted primarily on soils in flat no-till systems. Research results have been highly divergent, showing that plant uptake from nonincorporated broadcast-applied P and K fertilizer was greater than, less than, or equivalent to nutrient uptake from incorporated P and K fertilizer. For example, Singh et al. (1966) reported that P uptake from surface-applied fertilizer was equal to or greater than that from incorporated P fertilizer. It is thought that the greater P uptake observed in no-till systems is the result of higher soil moisture and accompanying root proliferation in no-till soil surfaces. While several researchers found K uptake to be adequate in crops under no-tillage (Triplett and Van Doren, 1969; Fink and Wesley,

1974), Estes (1972) reported significantly greater K uptake in no-till soils when compared to tilled soils. In contrast, Moncrief and Schulte (1981) found decreased K uptake from surface-applied fertilizer in no-till systems.

The variability in the investigators' results can be explained in part by (1) the soil moisture and temperature conditions and (2) the subsoil P and K test levels specific to study locations. It is expected that nutrient stratification will not adversely affect crop nutrient uptake and response under conditions of adequate surface moisture. Because reduced and no-till soils generally have a higher soil moisture level than conventionally tilled soils, roots are able to proliferate in the moist surface soil layer and efficiently extract nutrients from broadcast-applied fertilizers. However, during extended periods of dry weather, surface-applied P and K may become positionally unavailable. If subsoil moisture is adequate but subsoil P and K test levels are low, plant roots will not be able to extract adequate nutrients for optimum yields. Thus, nutrient stratification will not be favorable for crop growth when both low soil moisture and low subsoil fertility conditions prevail. Furthermore, with regard to ridge systems, P and K may not necessarily be readily available during the period of early crop growth when root systems are small. Lower soil P and K levels in the ridge or row zone, as were observed in my study, may limit possibly early P and K uptake. Based on the nutrient distribution patterns observed in our investigation, it is concluded that yield-limiting problems potentially could develop in ridge till-plant, ridge slot-plant, and flat no-till systems due to positional unavailability of nutrients.

SUMMARY

Distribution patterns of P and K in long-term conservation tillage systems were determined by intensive quantitative sampling of the upper 25-cm soil layer and subsequent laboratory analysis for available P and available K. Results of the study show that pronounced vertical stratification of P and K occurred in the ridge tillplant, ridge slot-plant, and flat no-till systems. Available P and K values for the upper 5-cm soil layer were, on the average, 3.5 times greater than those for the 5- to 15-cm soil layer. In the ridge till-plant and ridge slot-plant systems, localized high concentrations of P and K were frequently observed in the interrow zones. No marked row-interrow differences in soil P and K were detected in the flat no-till system. Based on the nutrient distribution patterns observed in this study, it is concluded that yield-limiting problems potentially could develop in ridge till-plant, ridge slot-plant, and flat no-till systems due to positional unavailability of nutrients.

GENERAL SUMMARY

With the increasing use of conservation tillage practices by crop producers, it is essential that tillage-induced changes in soil chemical properties be assessed. The objective of this investigation was to determine the effects of NH_3 and broadcast-applied P and K on soil chemical properties in long-term conservation tillage systems. Tillage systems evaluated included ridge till-plant, ridge slot-plant, and flat no-till systems.

Subsurface soil acidity resulting from repeated NH_3 application in long-term conservation tillage systems that do not disturb the NH_3 injection zone was studied by: (1) observation of the size, shape, and distribution of acidic zones in the field using a pH color indicator method and (2) intensive quantitative sampling of soil profiles with subsequent laboratory analysis for soil pH. Acidic soil zones created by the nitrification of the injected NH_3 were roughly circular in shape with 12- to 18-cm diameters. Soil pH of the acidic zones was generally 0.9 to 1.8 pH units lower than that of the surrounding bulk soil. In the ridge till-plant and ridge slot-plant systems studied, a distinct highly localized persistent acidic soil zone was detected in each interrow. Based on the extent and degree of acidity observed, it is concluded that yield-limiting problems due to acidification by continuous NH_3 applications is not likely in ridge management systems. In th flat no-till systems studied, numerous persistent acidic soil zones were observed scattered throughout each interrow. It is concluded that soil acidity problems due to long-term NH_3 usage potentially could

develop in no-till systems where NH_3 is not injected in the same vicinity each year. Efforts toward localized placement of N by the farm operator could effectively minimize potential problems due to the acidifying effects of NH_3 in conservation tillage systems.

Distribution patterns of P and K in long-term conservation tillage systems were determined by intensive quantitative sampling of soil profiles and subsequent laboratory analysis for available P and available K. Results of the study show that pronounced vertical stratification of P and K occurred in the ridge till-plant, ridge slot-plant, and flat no-till systems. Available P and K values for the upper 5-cm soil layer were, on the average, 3.5 times greater than those for the 5- to 15-cm soil layer. In the ridge till-plant and ridge slot-plant systems, localized high concentrations of P and K were frequently observed in the interrow zones. No marked row-interrow differences in soil P and K were detected in the flat no-till system. Based on the nutrient distribution patterns observed in this study, it is concluded that yield-limiting problems potentially could develop in ridge till-plant, ridge slot-plant, and flat no-till systems due to positional unavailability of nutrients.

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Finally, the author dedicates this dissertation to the late Jim Doerr who had dreamed one day of receiving his Ph.D. at Iowa State University.

APPENDIX A: SOIL pH DISTRIBUTIONS

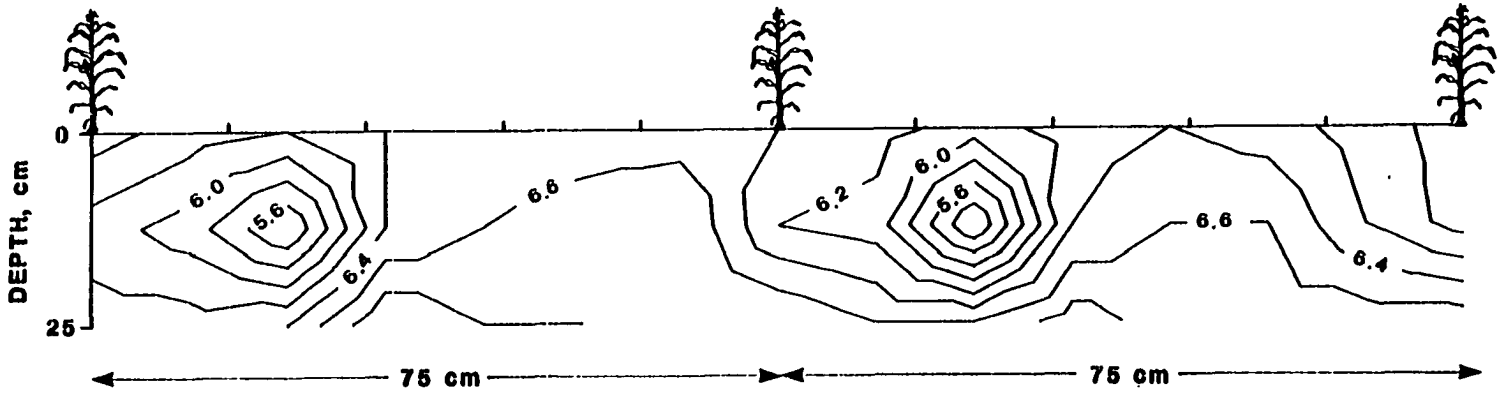

Figure A1. Soil pH distribution at Site A, Area I, with NH_3 in 1983

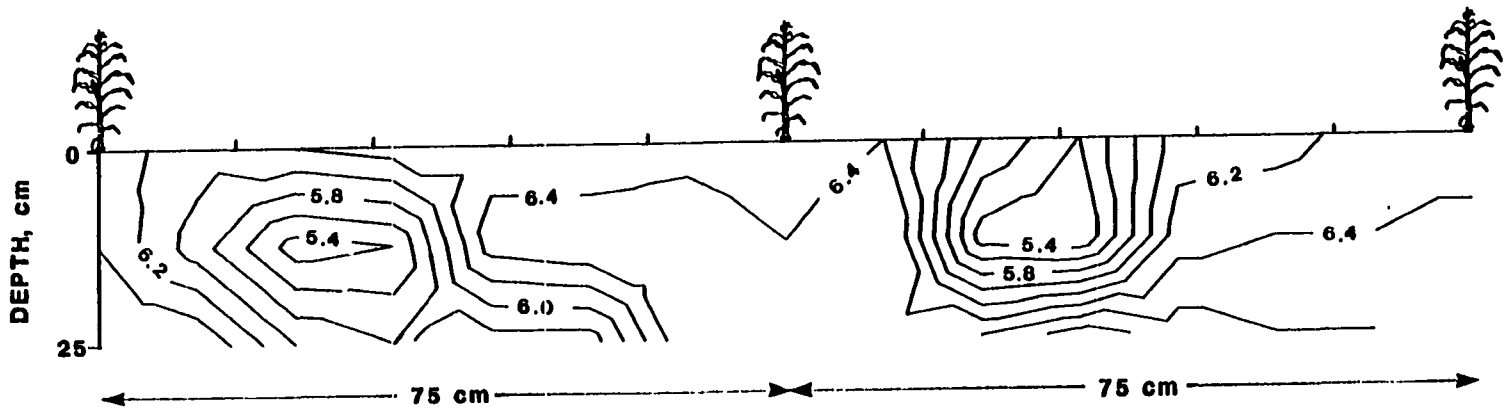

Figure A2. Soil pH distribution at Site B, Area I, with NH_3 in 1983

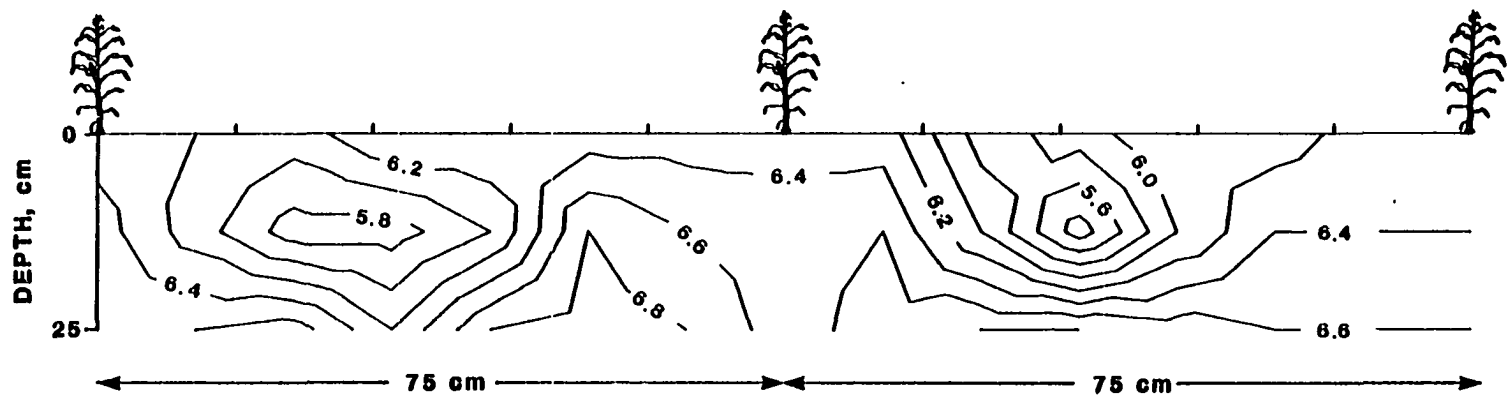

Figure A3. Soil pH distribution at Site C, Area I, with NH_3 in 1983

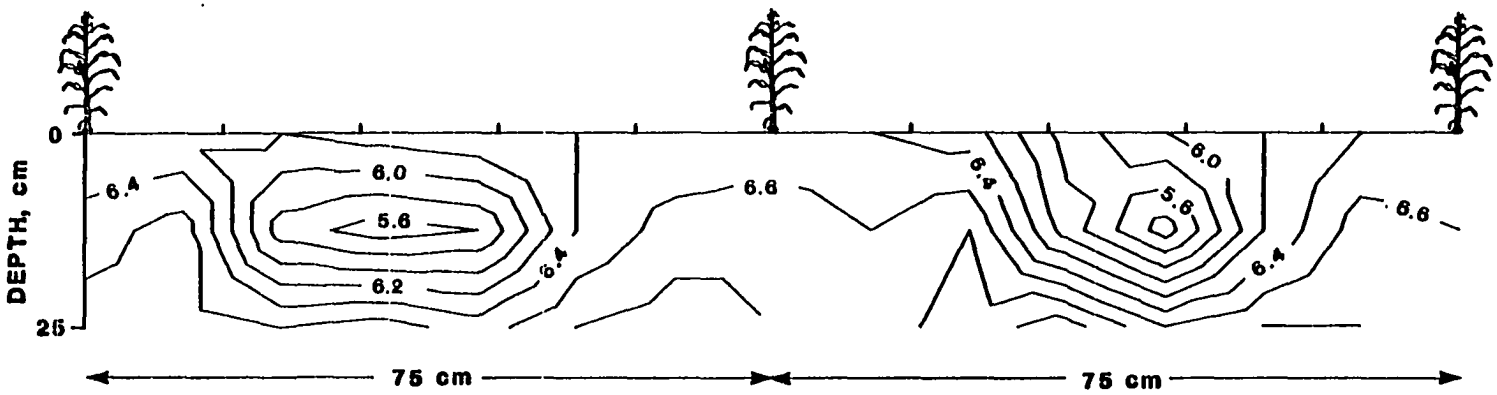

Figure A4. Soil pH distribution at Site D, Area I, with NH_3 in 1983

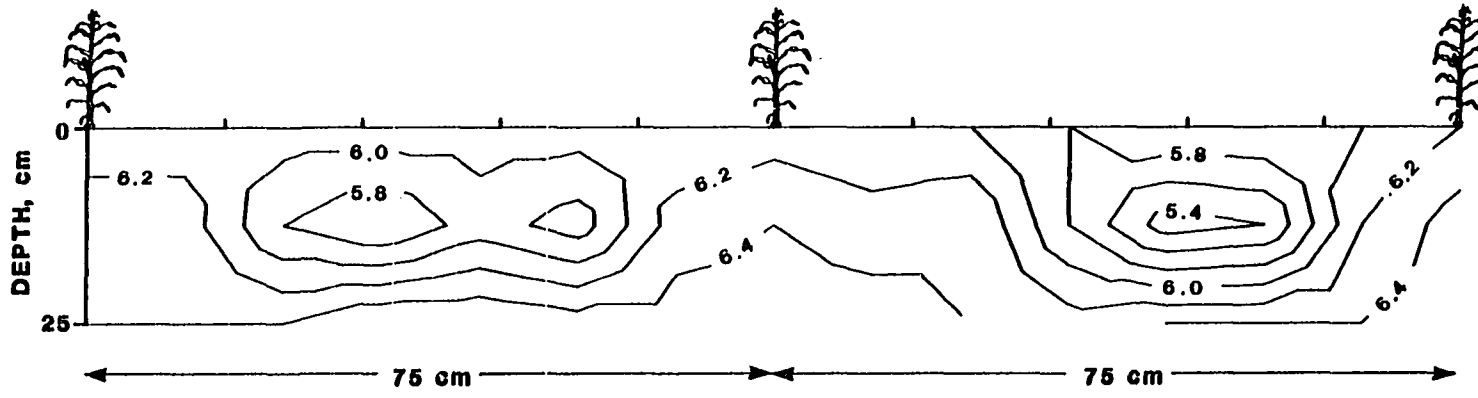

Figure A5. Soil pH distribution at Site E, Area I, with NH_3 in 1983

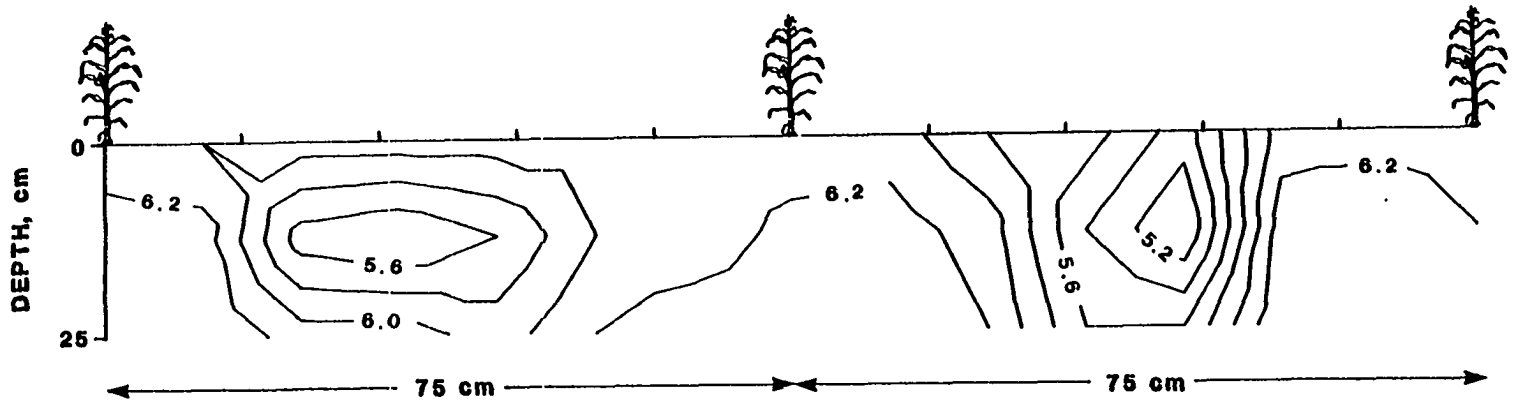

Figure A6. Soil pH distribution at Site F, Area I, with NH_3 in 1983

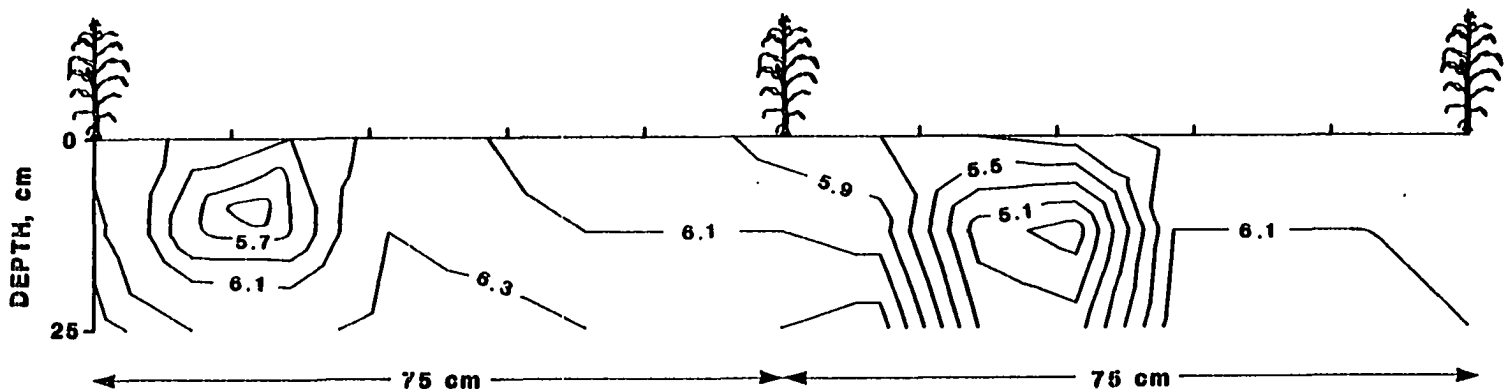

Figure A7. Soil pH distribution at Site A, Area II, with NH_3 in 1983

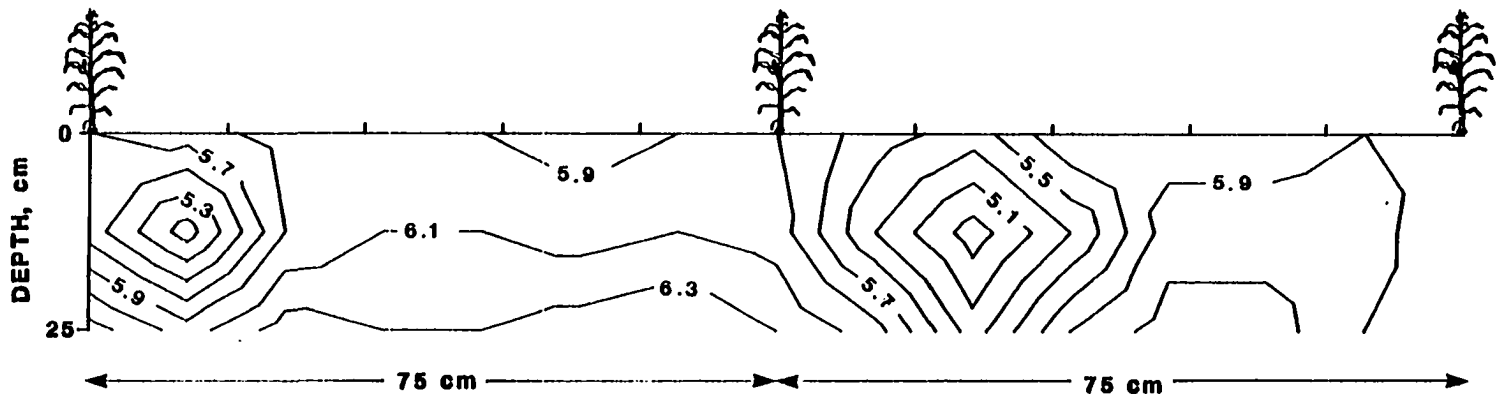

Figure A8. Soil pH distribution at Site B, Area II, with NH_3 in 1983

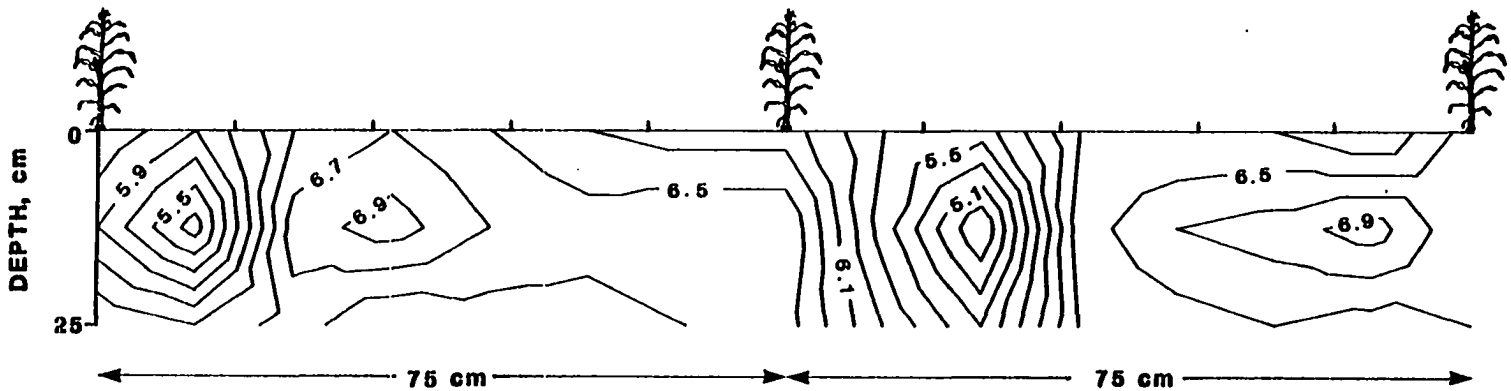

Figure A9. Soil pH distribution at Site C, Area II, with NH_3 in 1983

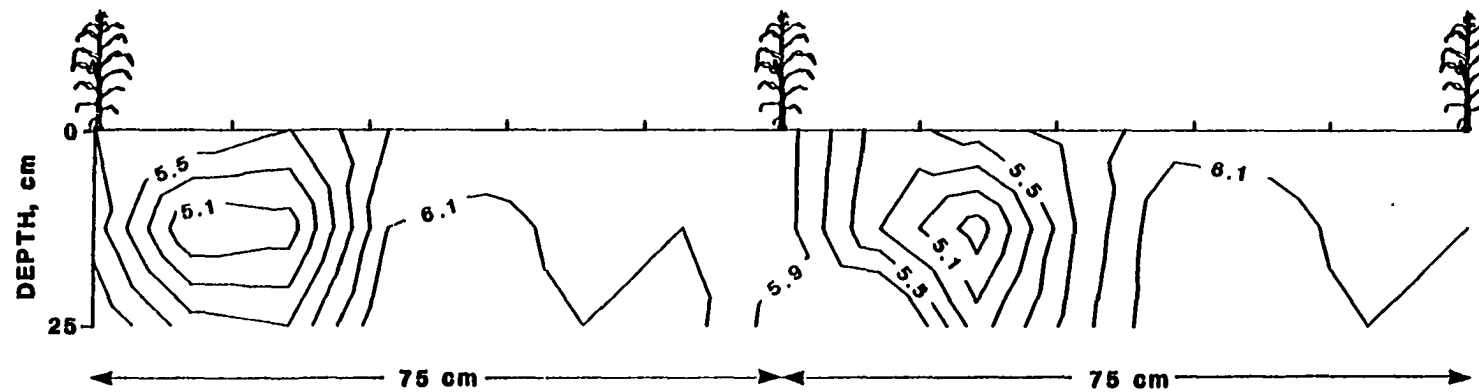

Figure A10. Soil pH distribution at Site D, Area II, with NH_3 in 1983

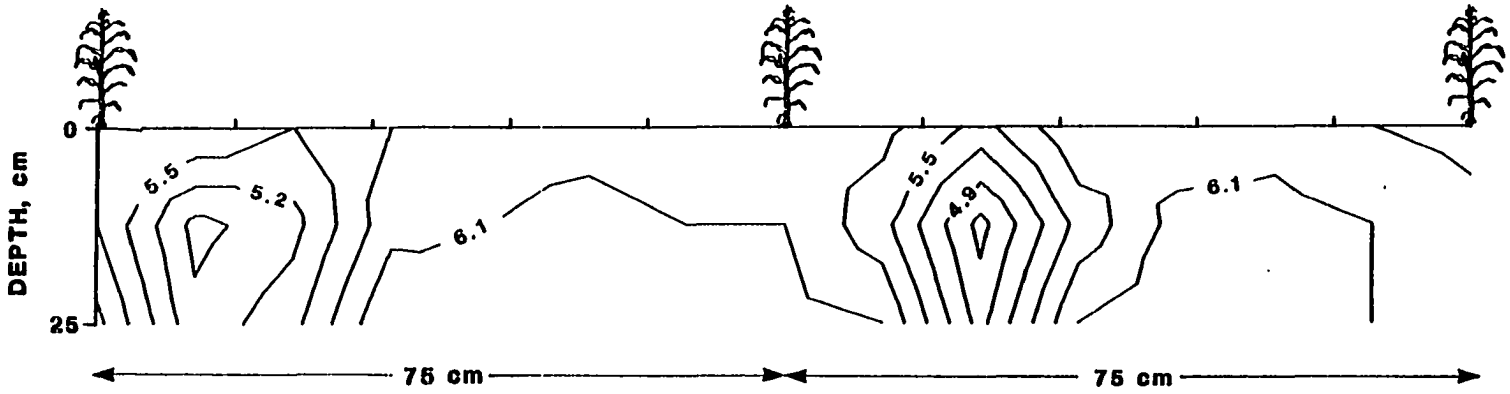

Figure A11. Soil pH distribution at Site E, Area II, with NH_3 in 1983

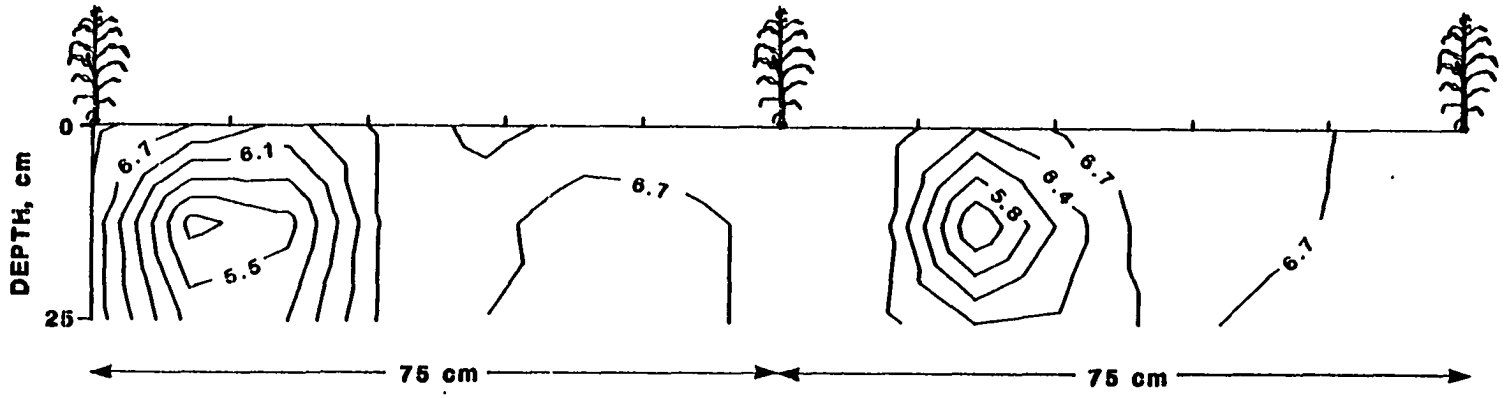

Figure A12. Soil pH distribution at Site F, Area II, with NH_3 in 1983

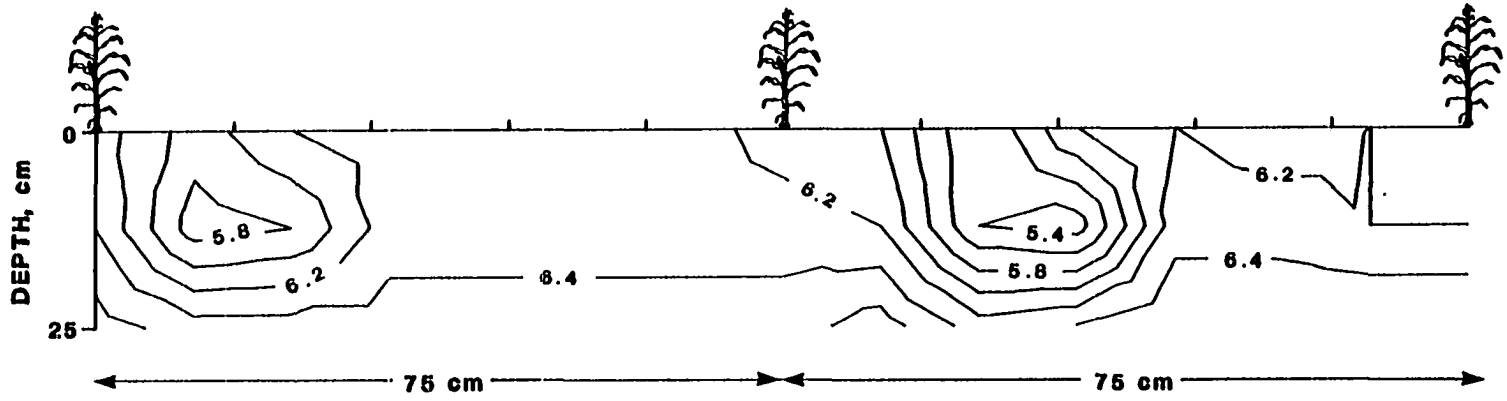

Figure A13. Soil pH distribution at Site A, Area II, without NH_3 in 1984

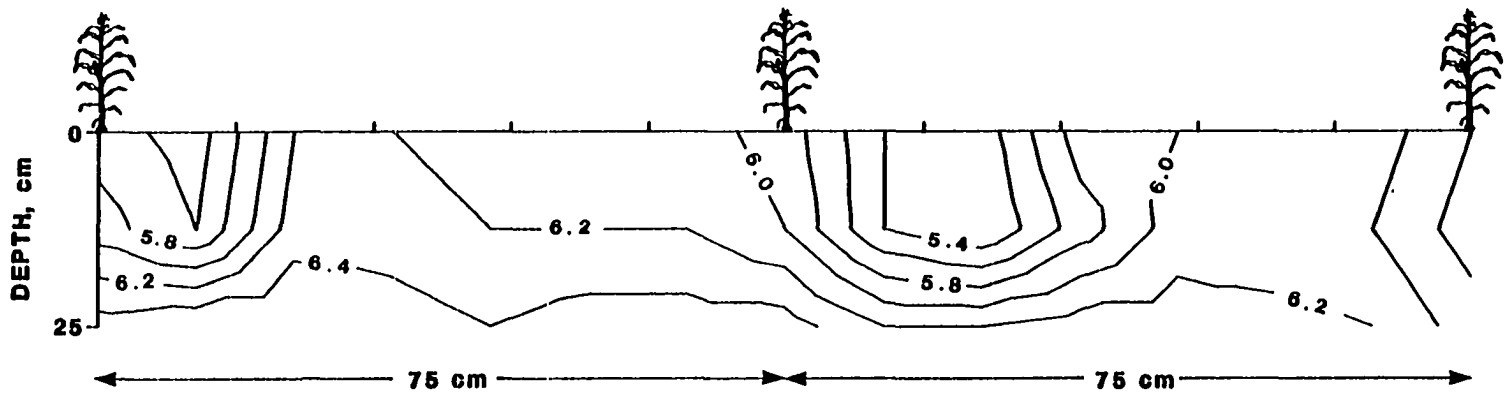

Figure A14. Soil pH distribution at Site B, Area II, without NH_3 in 1984

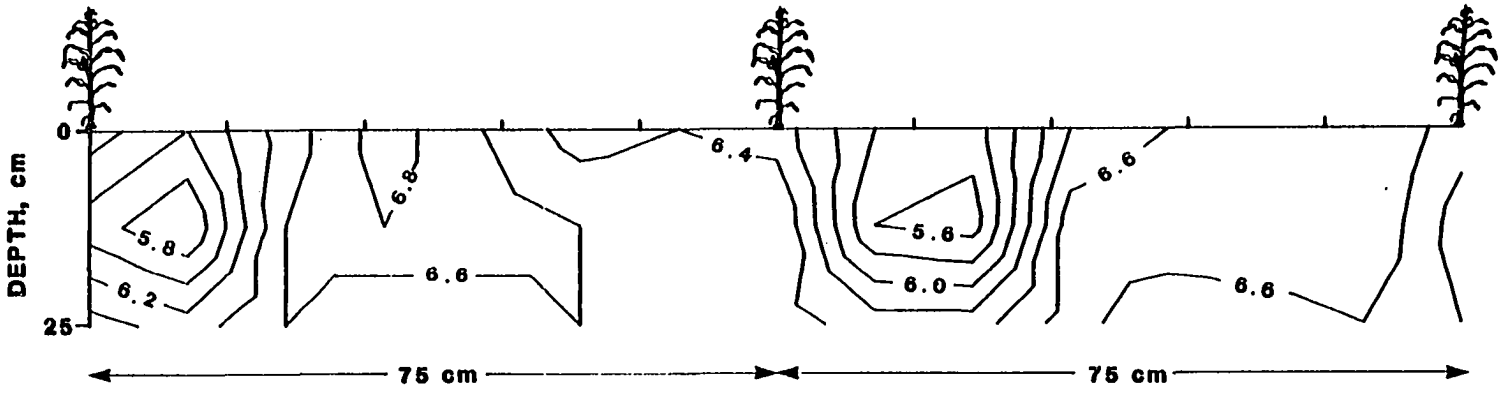

Figure A15. Soil pH distribution at Site C, Area II, without NH_3 in 1984

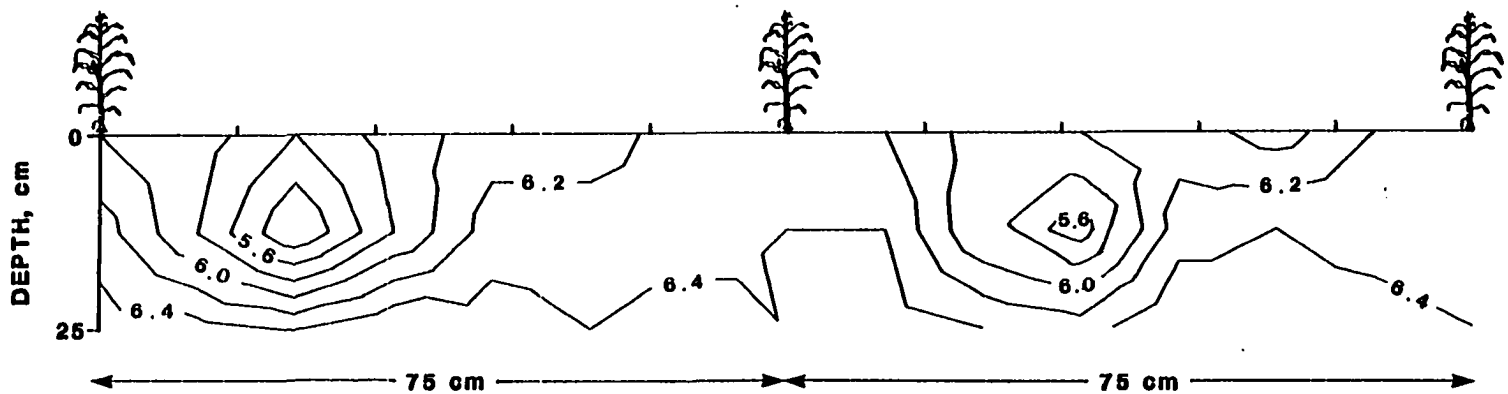

Figure A16. Soil pH distribution at Site D, Area II, without NH_3 in 1984

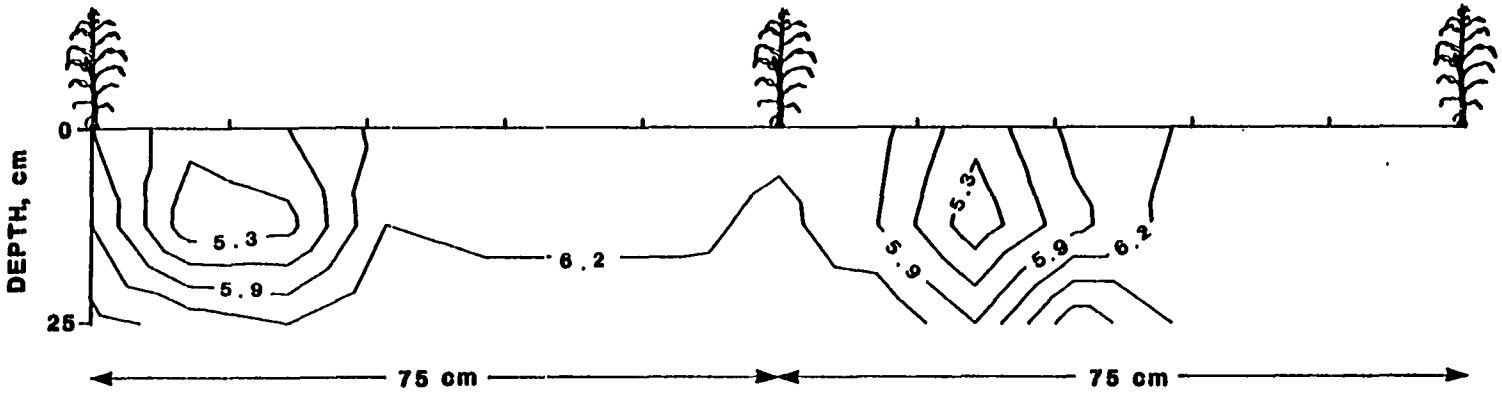

Figure A17. Soil pH distribution at Site E, Area II, without NH_3 in 1984

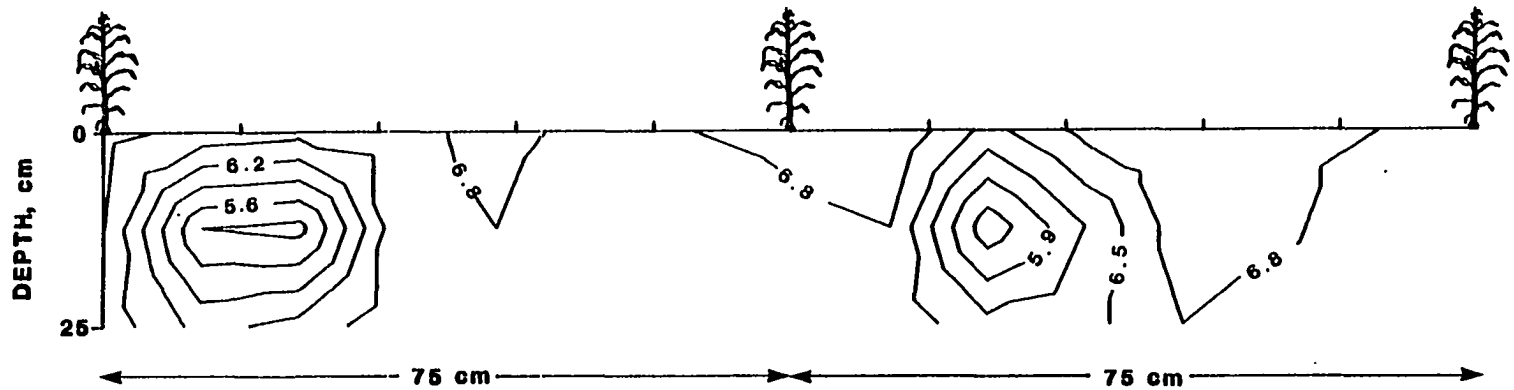

Figure A18. Soil pH distribution at Site F, Area II, without NH_3 in 1984

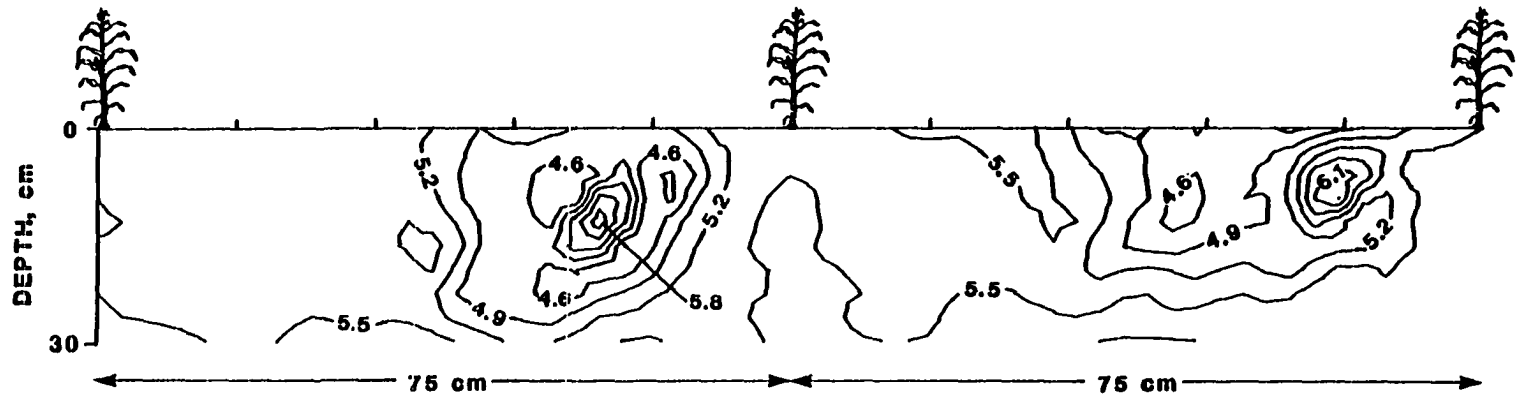

Figure A19. In situ soil pH distribution at Site G, Area II, with NH_3 in 1984

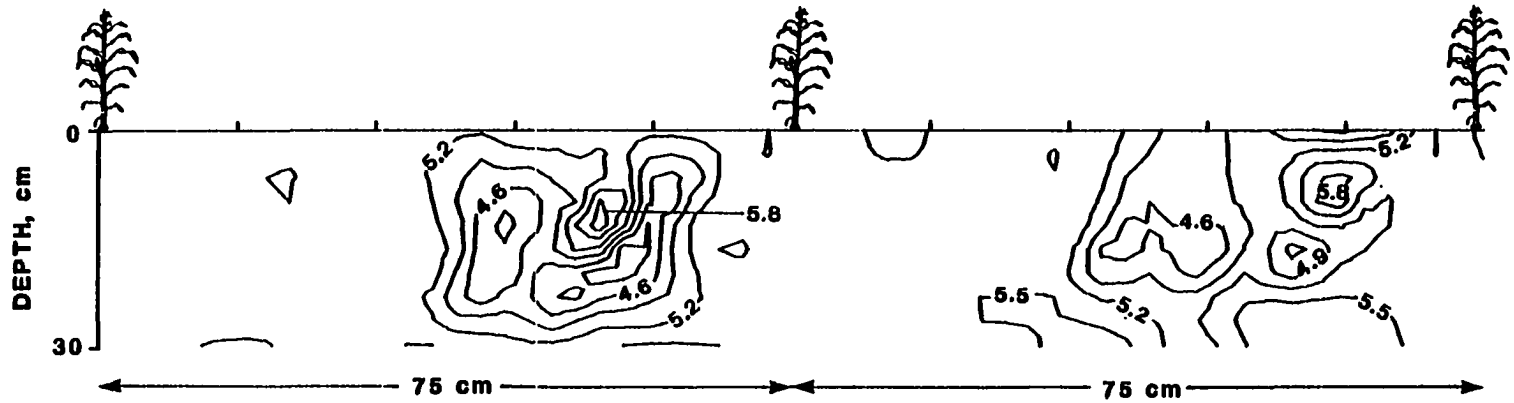

Figure A20. In situ soil pH distribution at Site H, Area II, with NH_3 in 1984

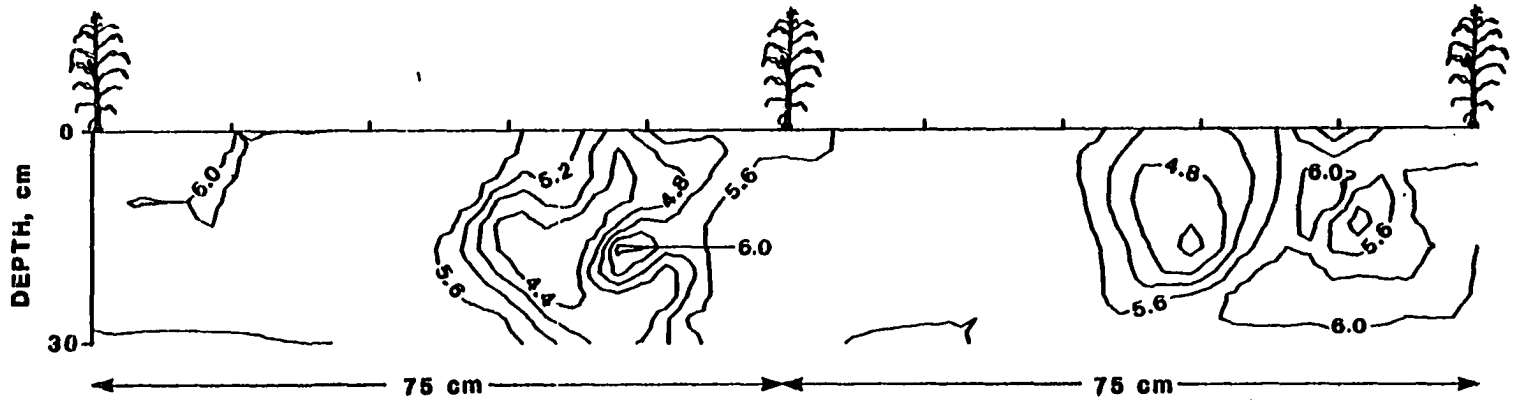

Figure A21. In situ soil pH distribution at Site I, Area II, with NH_3 in 1984

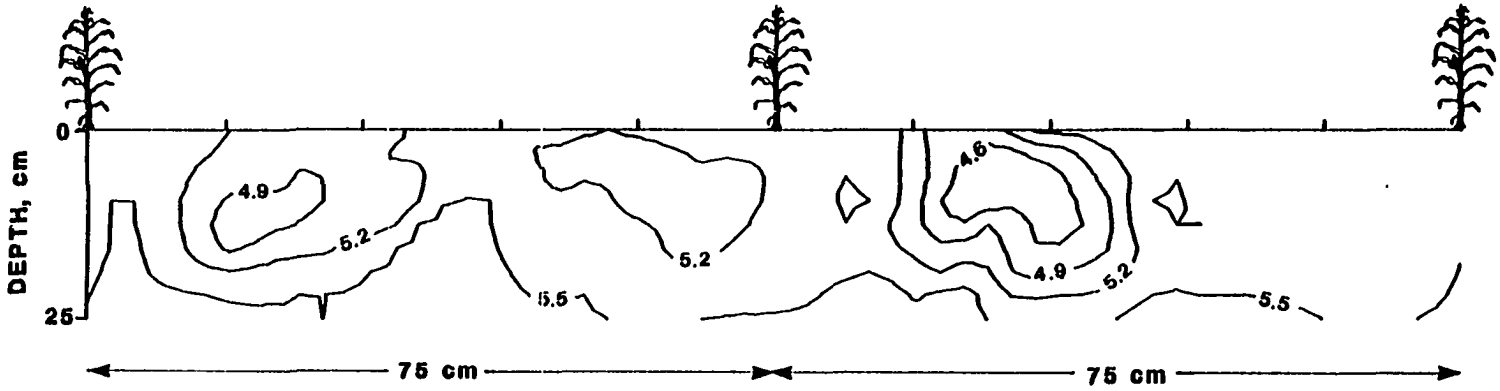

Figure A22. In situ soil pH distribution at Site D, Area II, without NH_3 in 1984

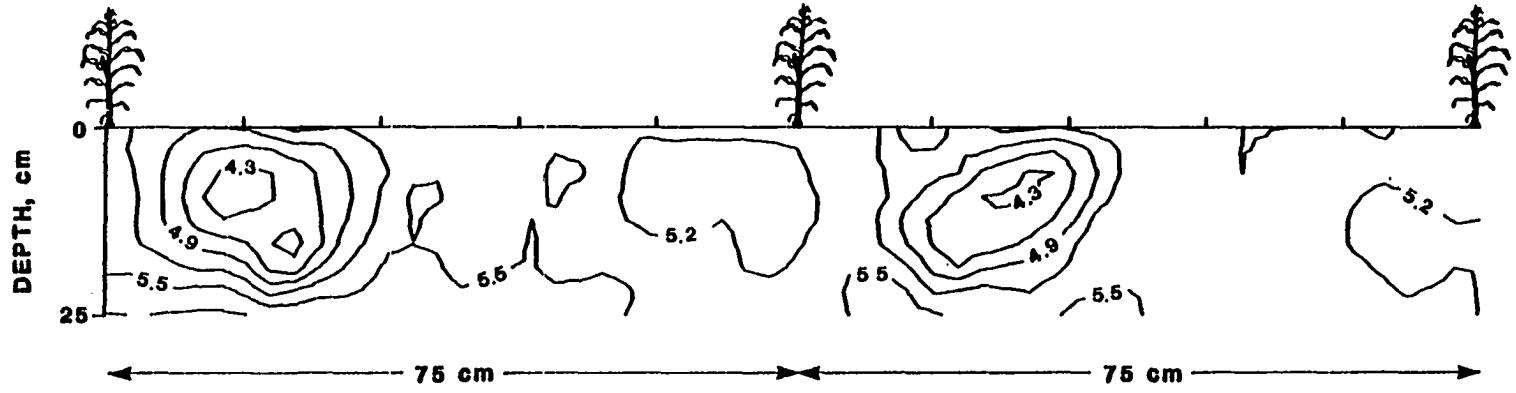

Figure A23. In situ soil pH distribution at Site E, Area II, without NH_3 in 1984

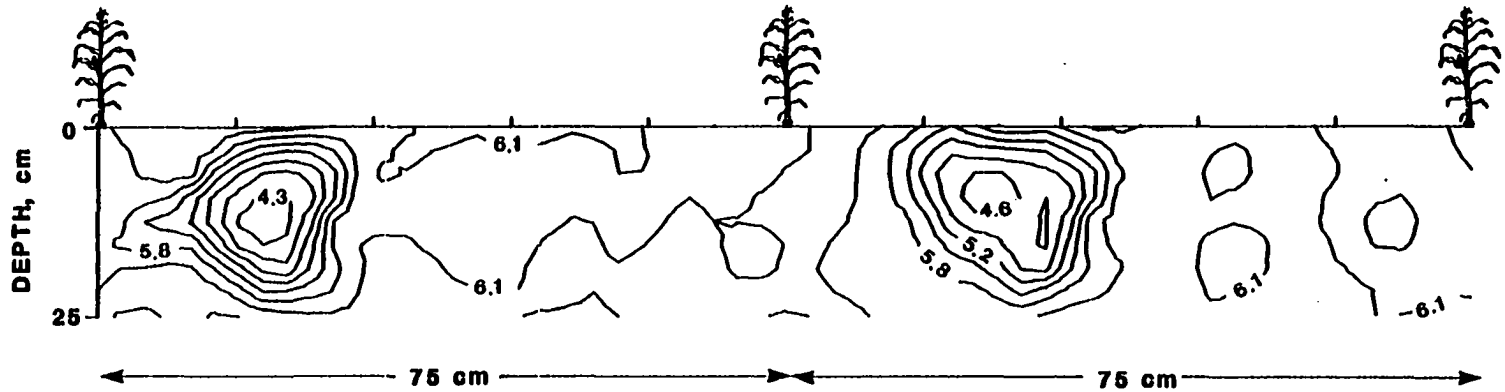

Figure A24. In situ soil pH distribution at Site F, Area II, without NH_3 in 1984

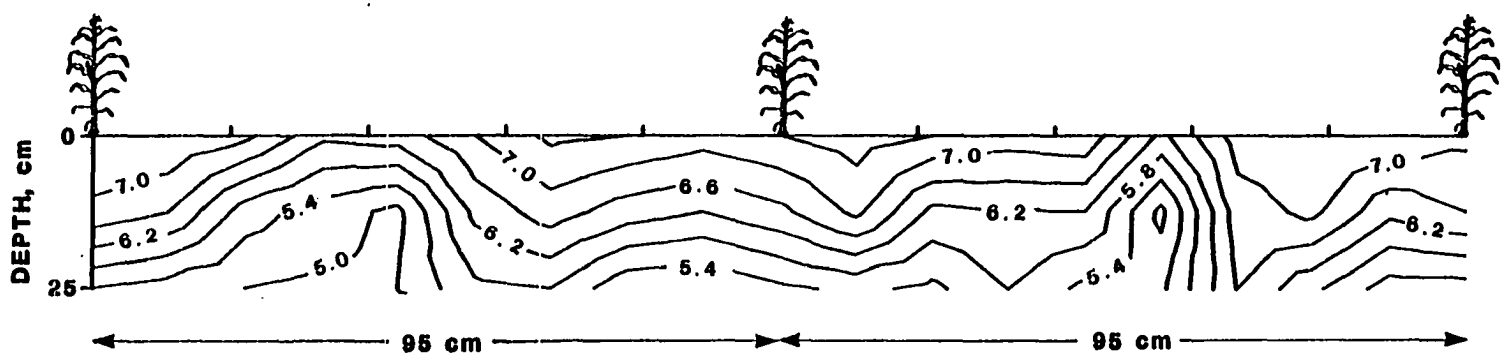

Figure A25. Soil pH distributions at Site A, Area III, with NH_3 in 1983

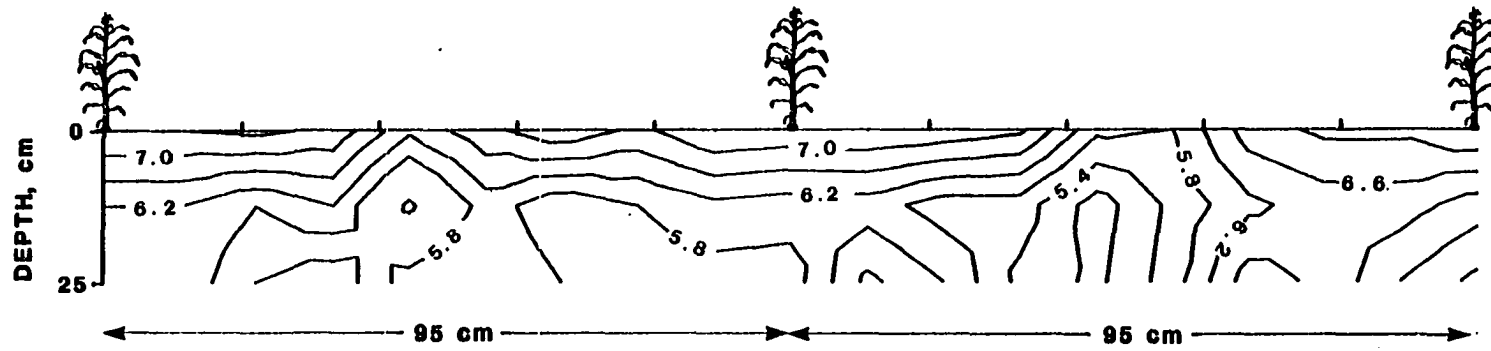

Figure A26. Soil pH distribution at Site B, Area III, with NH_3 in 1983

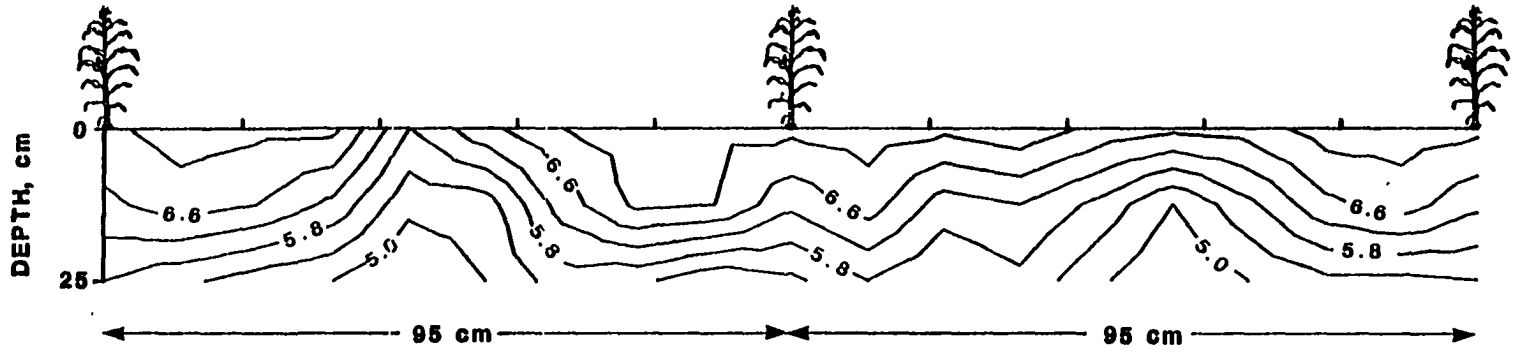

Figure A27. Soil pH distribution at Site C, Area III, with NH_3 in 1983

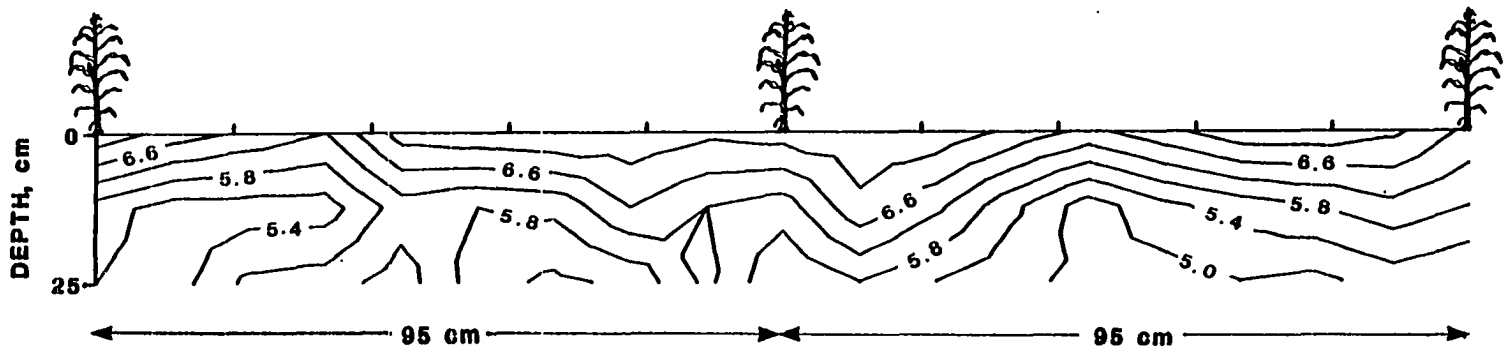

Figure A28. Soil pH distribution at Site D, Area III, with NH_3 in 1983

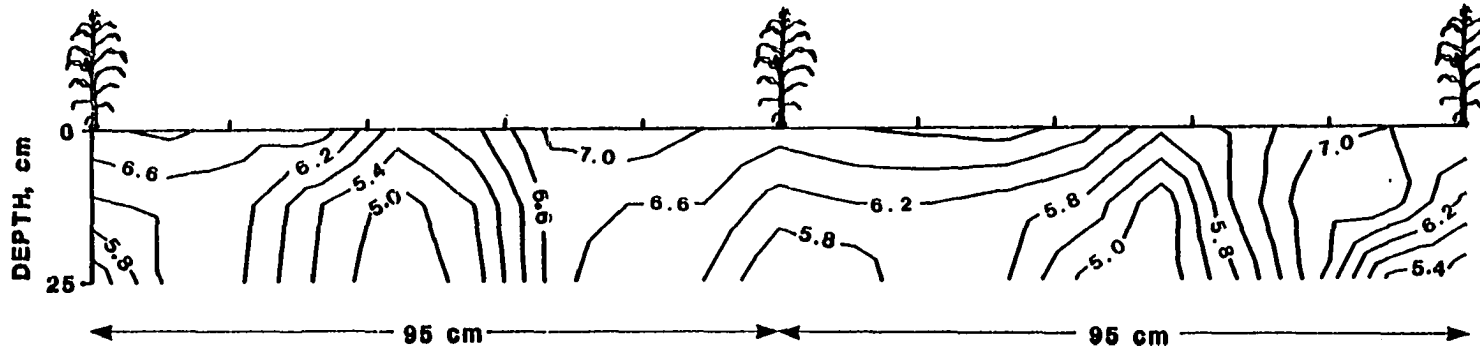

Figure A29. Soil pH distribution at Site E, Area III, with NH_3 in 1983

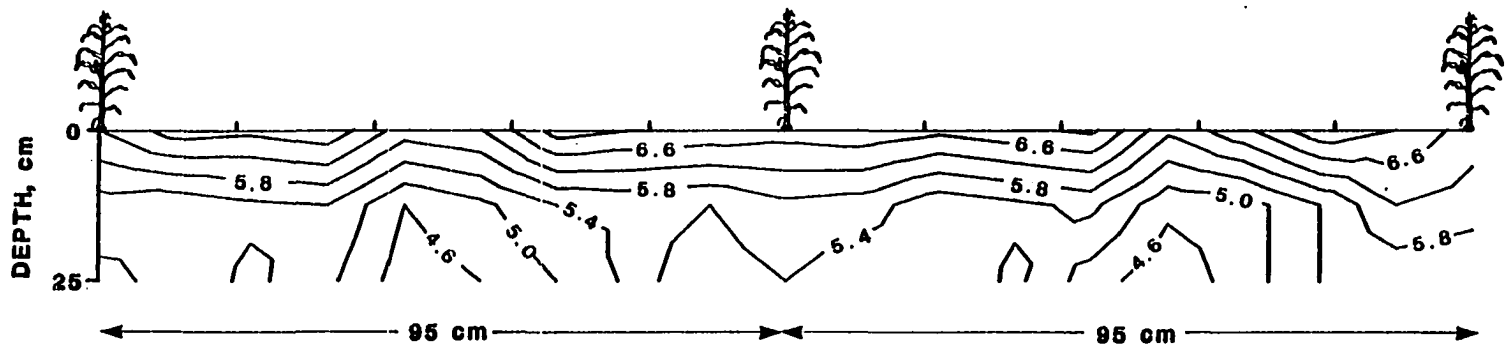

Figure A30. Soil pH distribution at Site F, Area III, with NH_3 in 1983

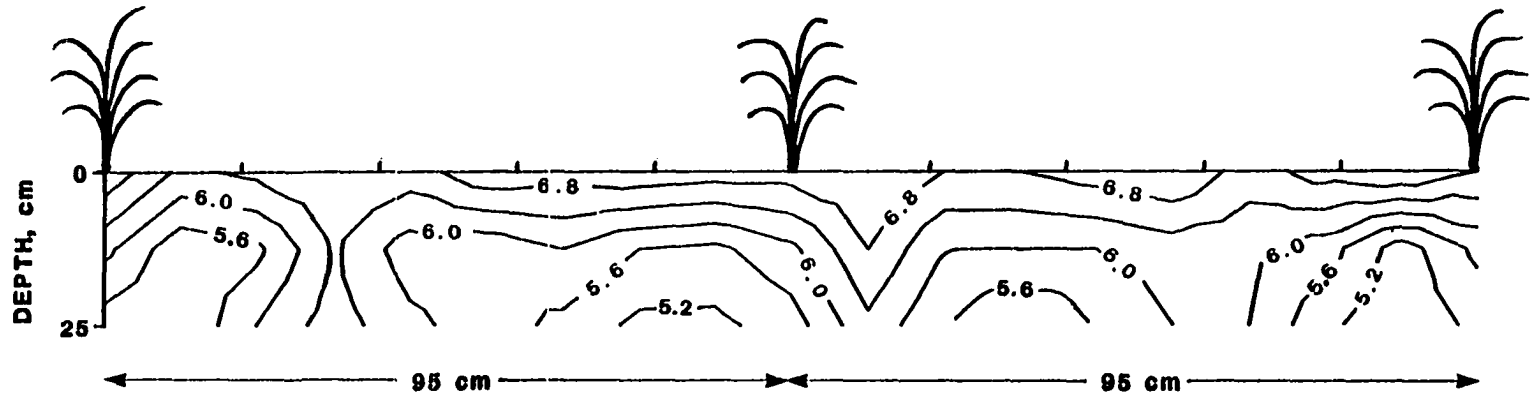

Figure A31. Soil pH distribution at Site A, Area IV, without NH_3 in 1983

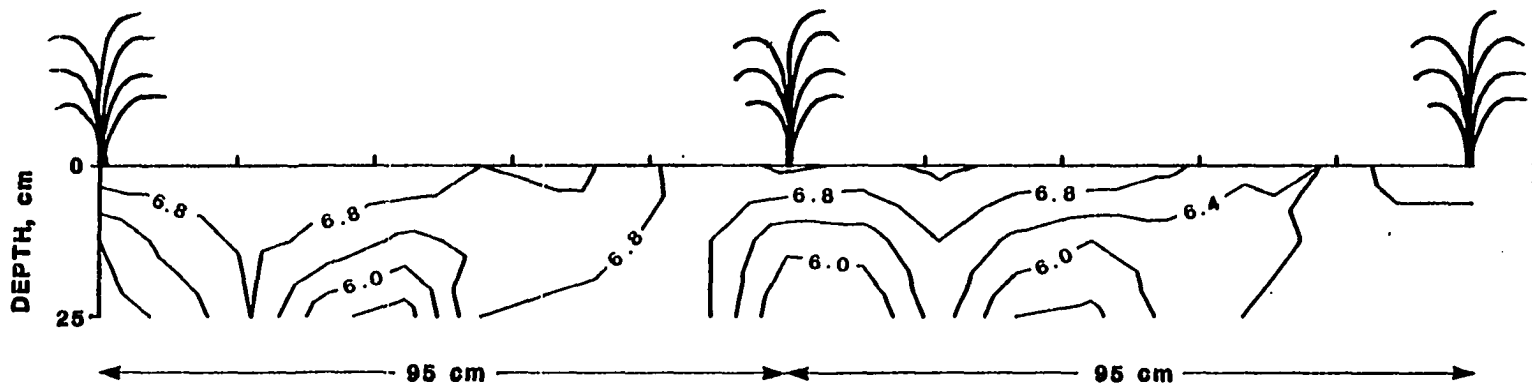

Figure A32. Soil pH distribution at Site B, Area IV, without NH_3 in 1983

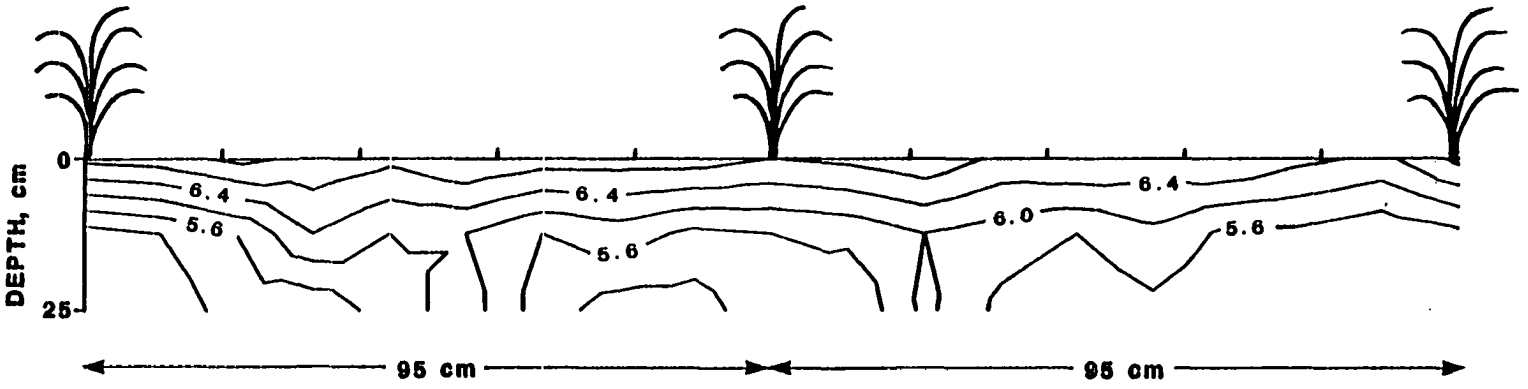

Figure A33. Soil pH distribution at Site C, Area IV, without NH_3 in 1983

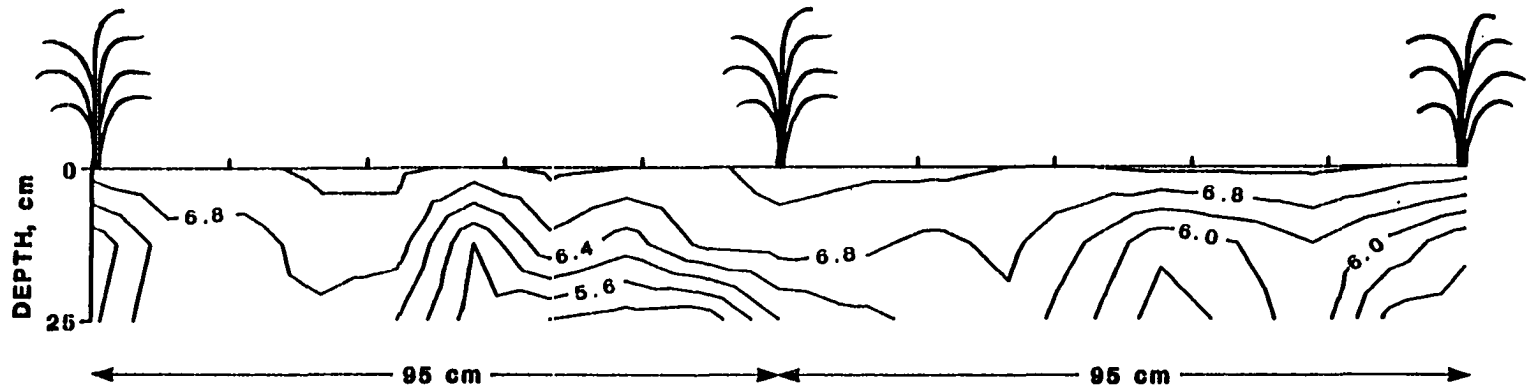

Figure A34. Soil pH distribution at Site D, Area IV, without NH_3 in 1983

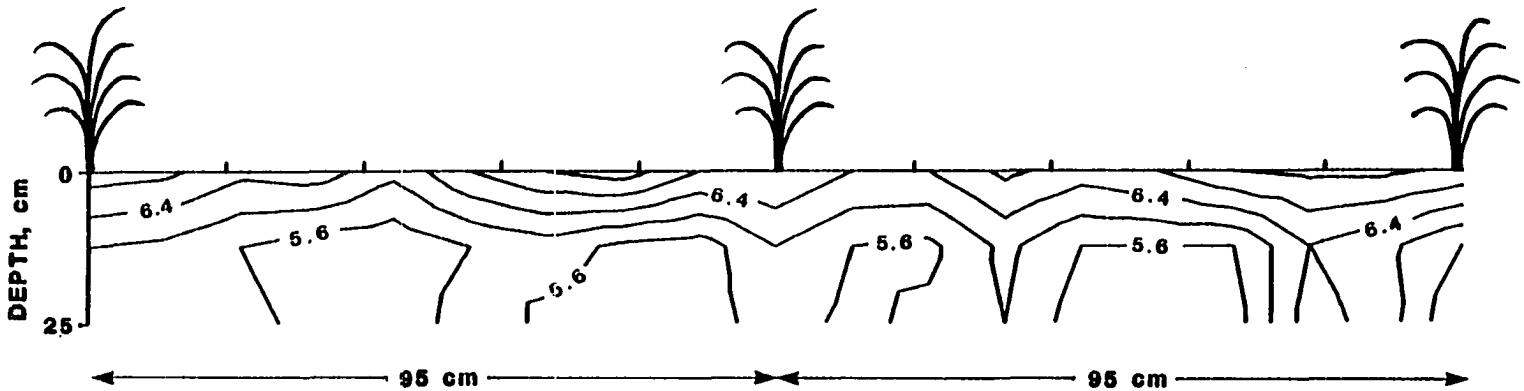

Figure A35. Soil pH distribution at Site E, Area IV, without NH_3 in 1983

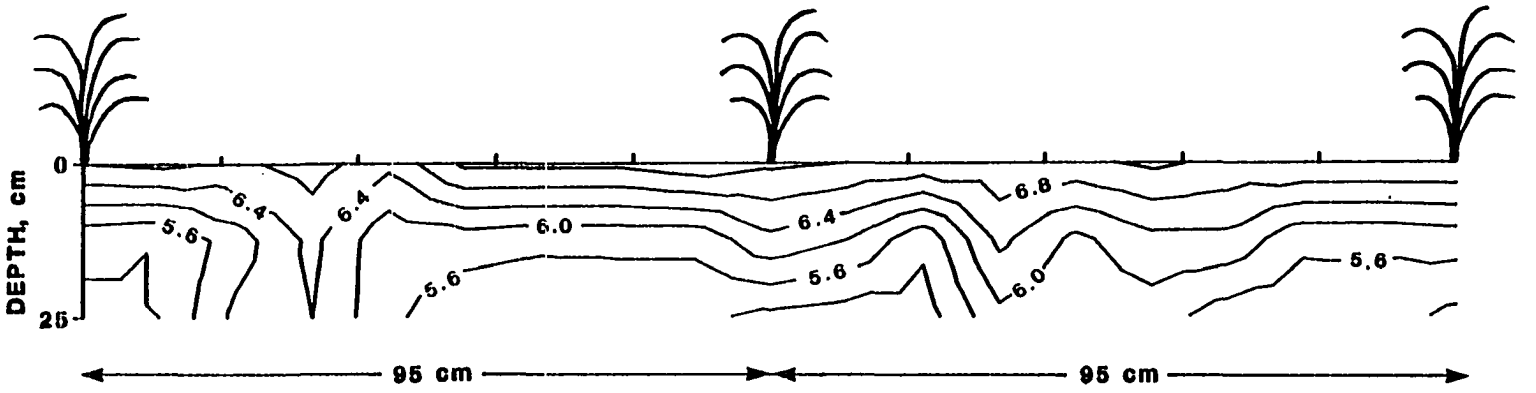

Figure A36. Soil pH distribution at Site F, Area IV, without NH_3 in 1983

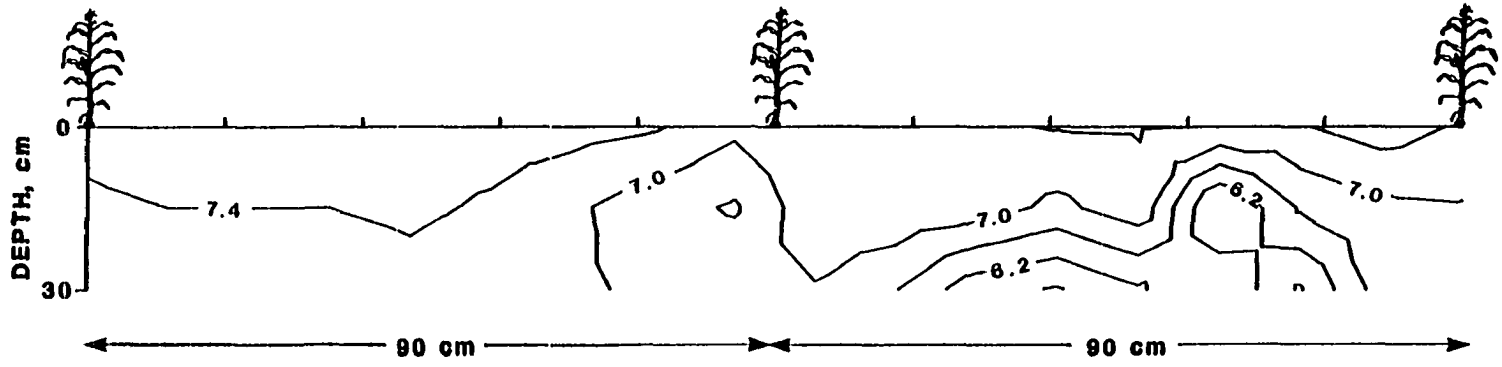

Figure A37. Soil pH distribution at Site A, Area V, with NH_3 in 1984

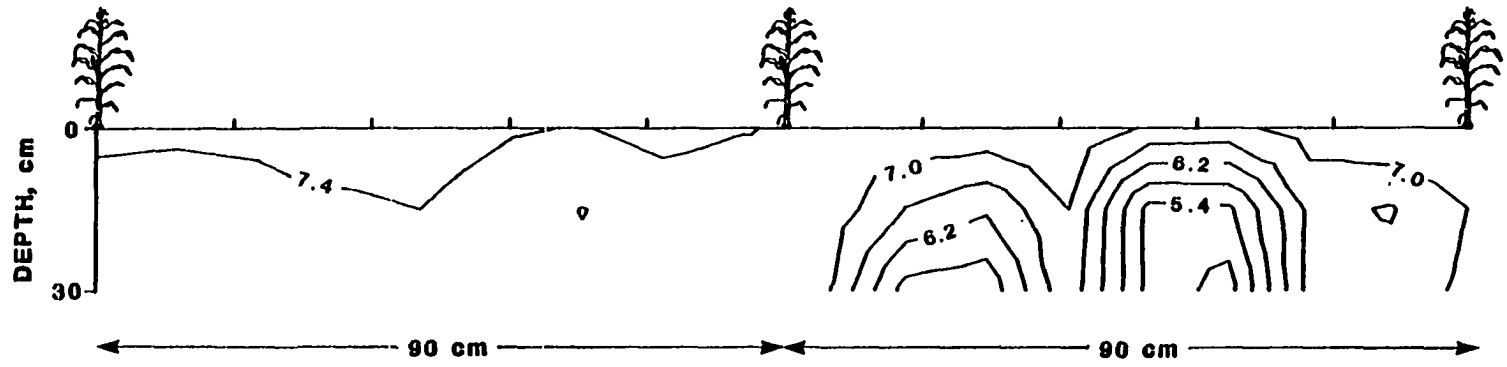

Figure A38. Soil pH distribution at Site B, Area V, with NH_3 in 1984

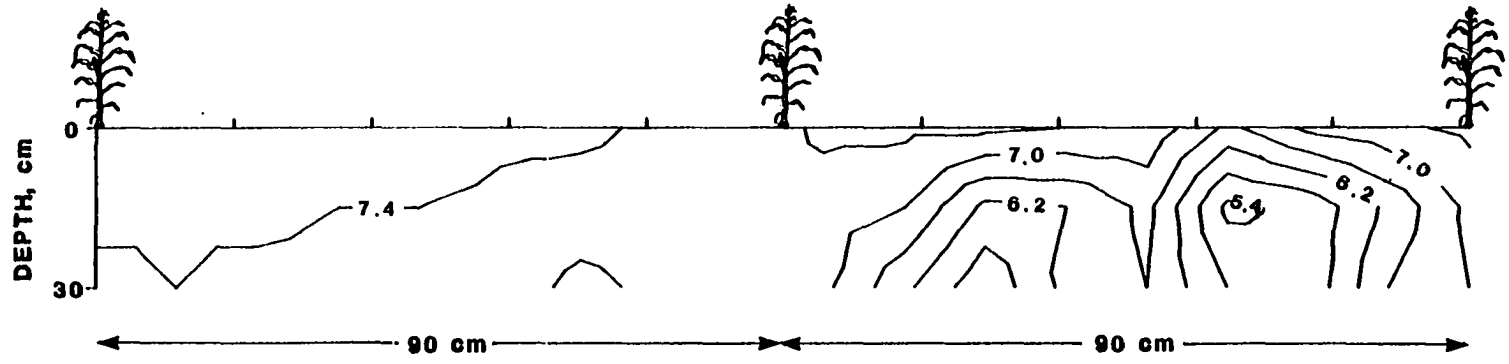

Figure A39. Soil pH distribution at Site C, Area V, with NH_3 in 1984

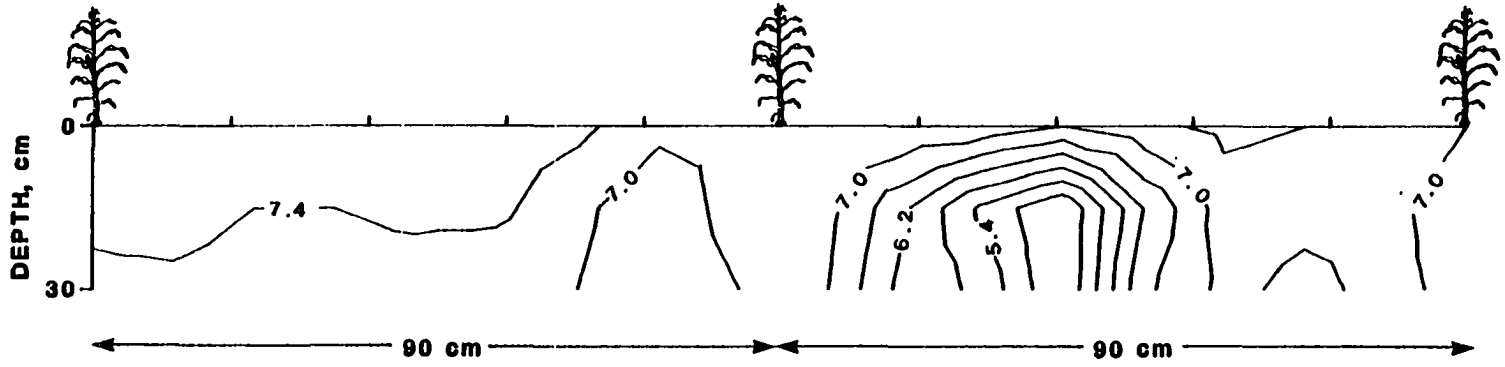

Figure A40. Soil pH distribution at Site D, Area V, with NH_3 in 1984

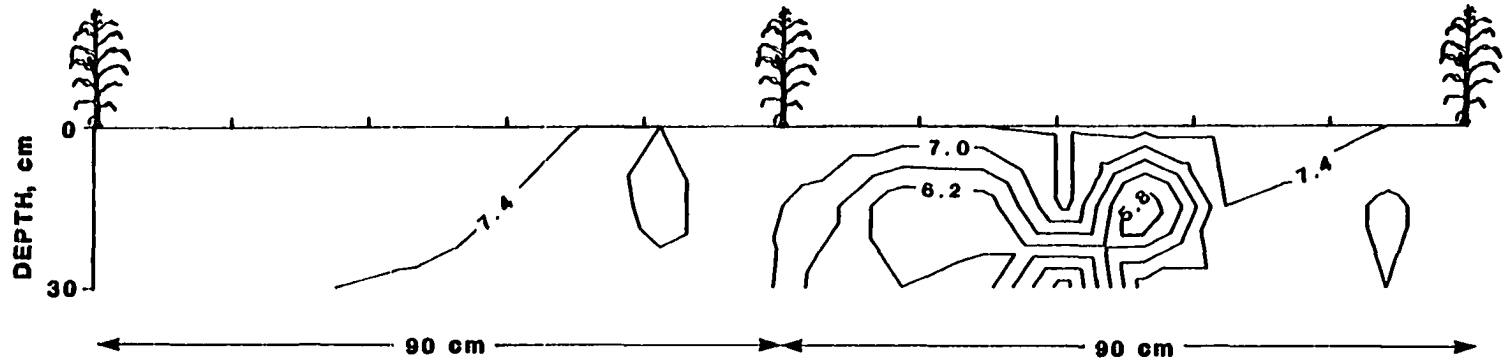

Figure A41. Soil pH distribution at Site E, Area V, with NH_3 in 1984

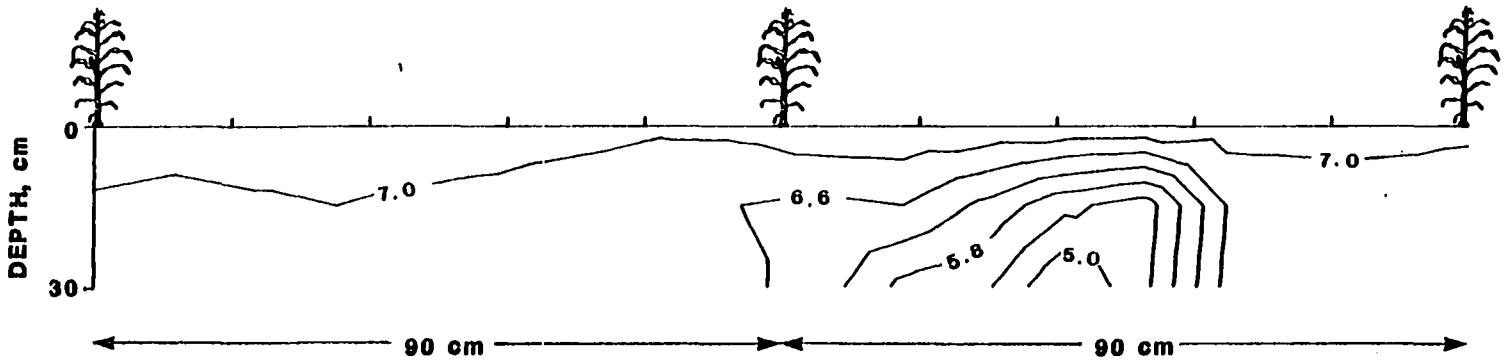

Figure A42. Soil pH distribution at Site F, Area V, with NH_3 in 1984

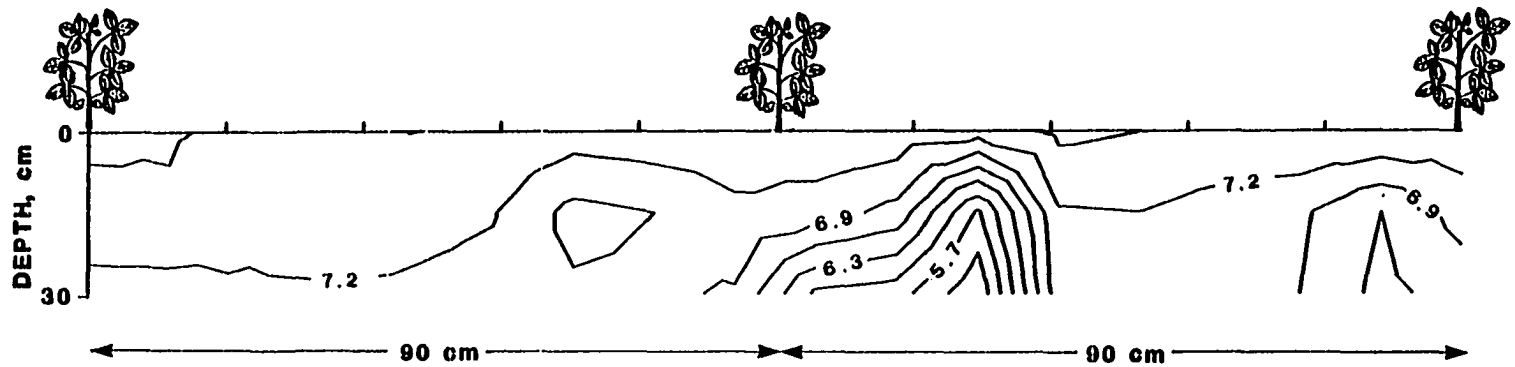

Figure A43. Soil pH distribution at Site A, Area VI, without NH_3 in 1984

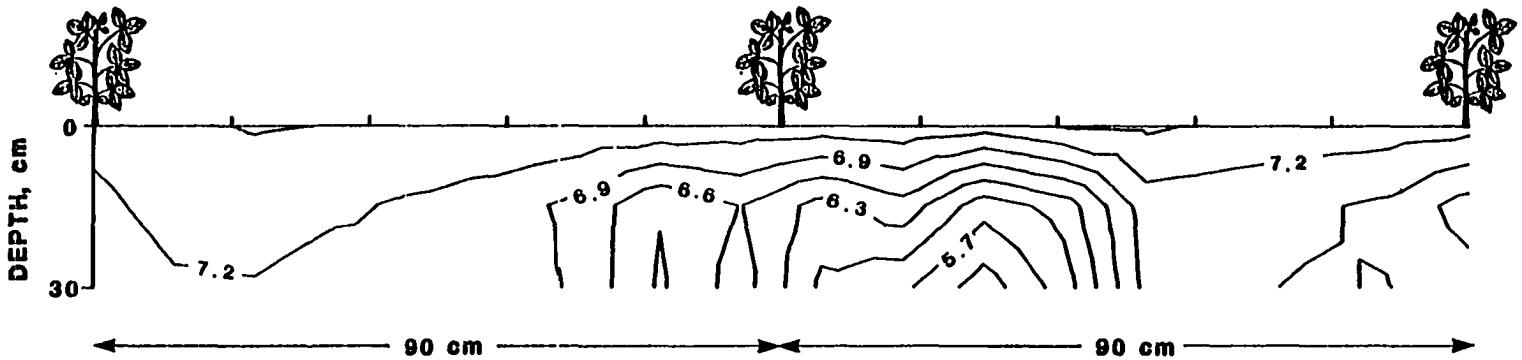

Figure A44. Soil pH distribution at Site B, Area VI, without NH_3 in 1984

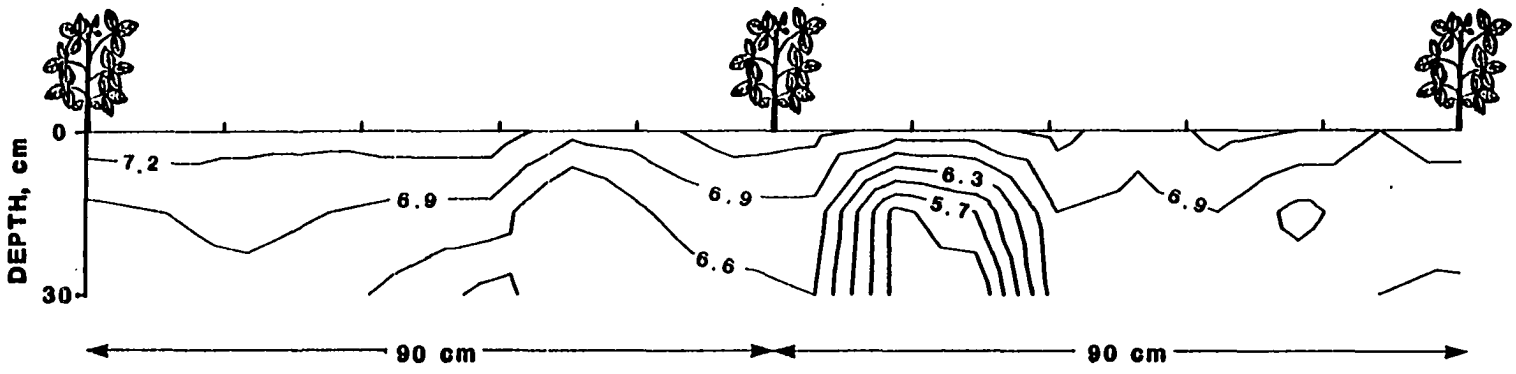

Figure A45. Soil pH distribution at Site C, Area VI, without NH_3 in 1984

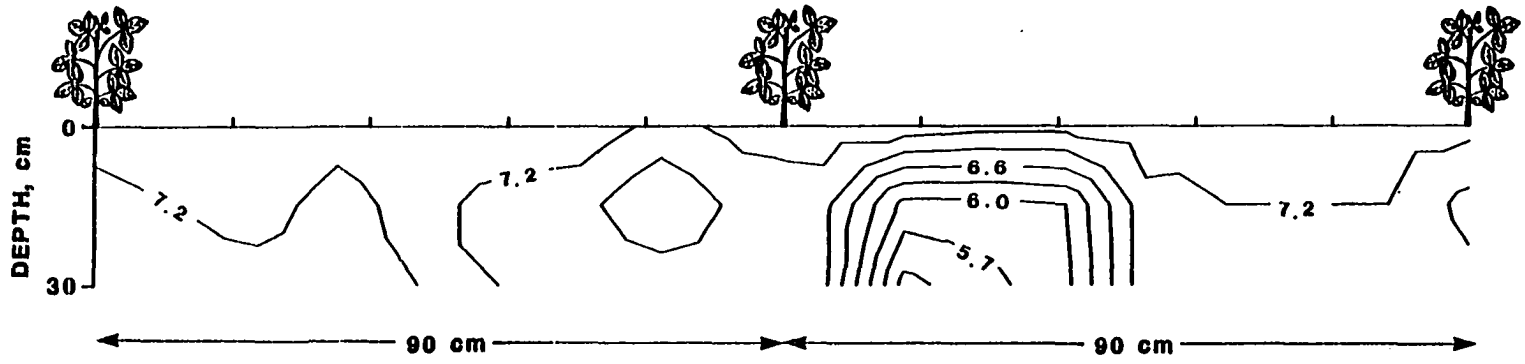

Figure A46. Soil pH distribution at Site D, Area VI, without NH_3 in 1984

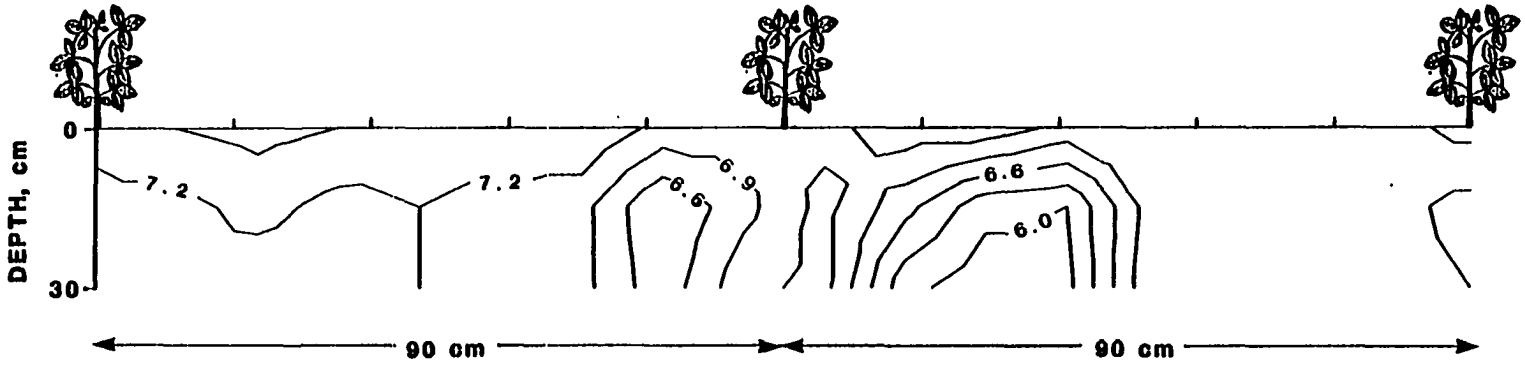

Figure A47. Soil pH distribution at Site E, Area VI, without NH_3 in 1984

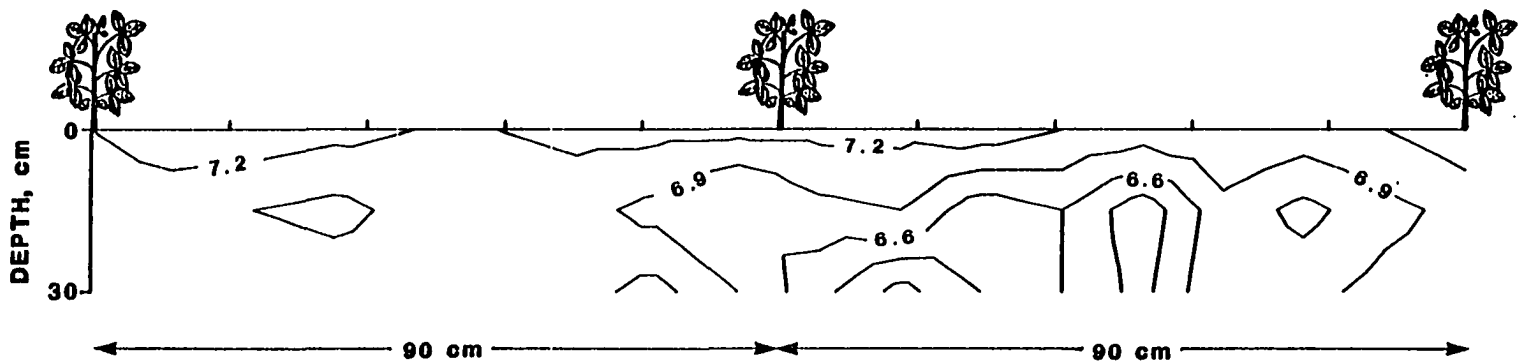

Figure A48. Soil pH distribution at Site F, Area VI, without NH_3 in 1984

APPENDIX B: AVAILABLE PHOSPHORUS DISTRIBUTIONS

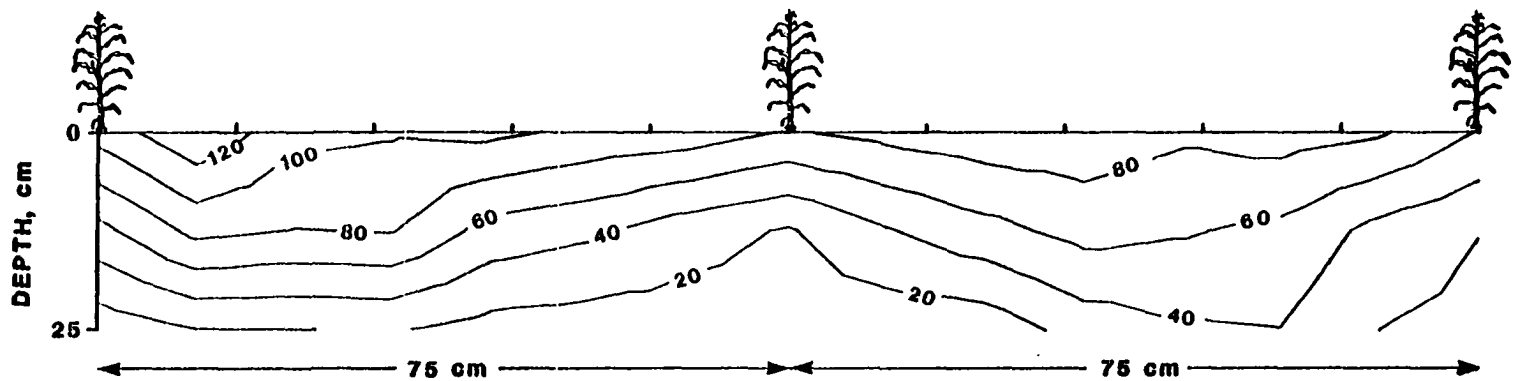

Figure B1. Available phosphorus distribution at Site A, Area I

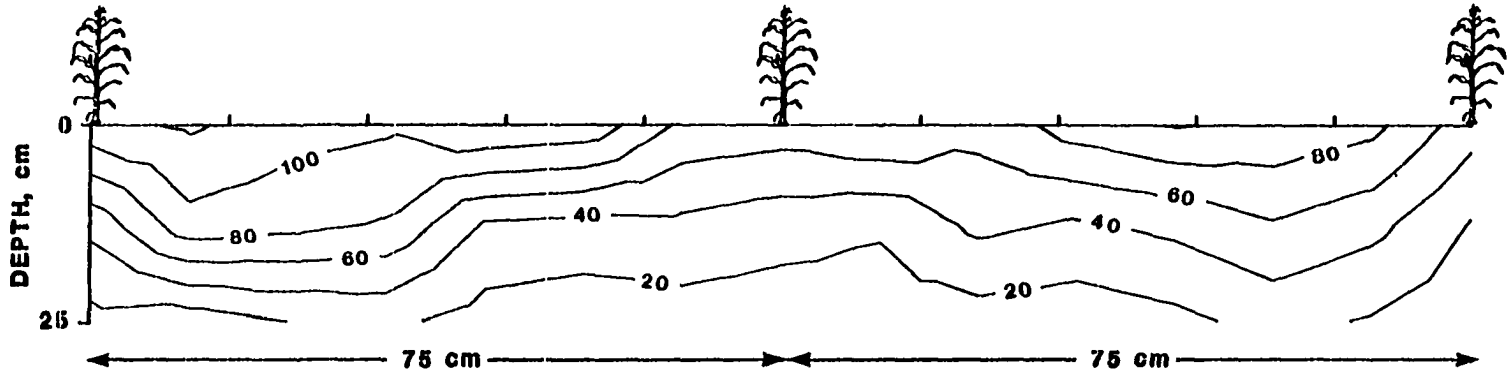

Figure B2. Available phosphorus distribution at Site B, Area I

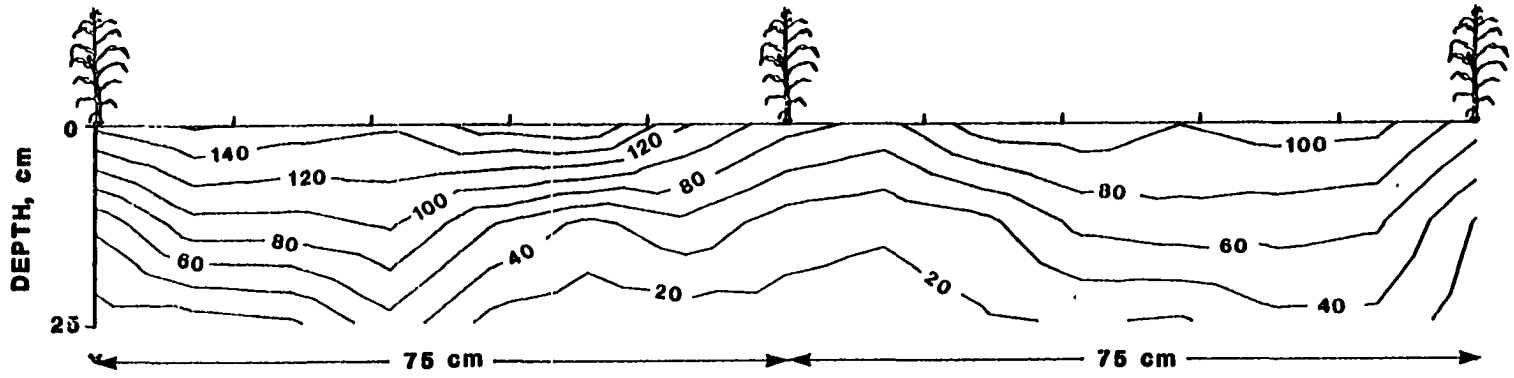

Figure B3. Available phosphorus distribution at Site C, Area I

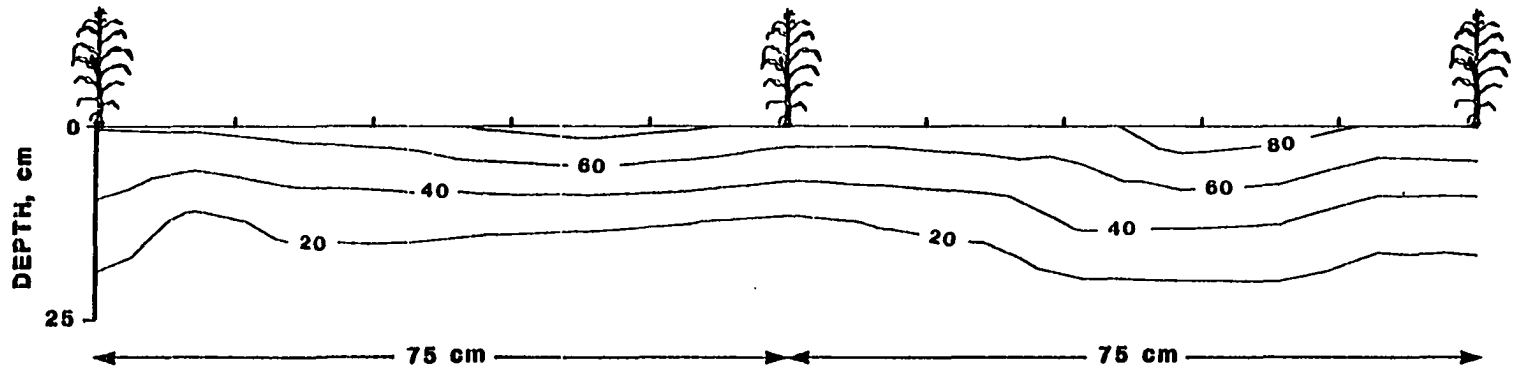

Figure B4. Available phosphorus distribution at Site D, Area I

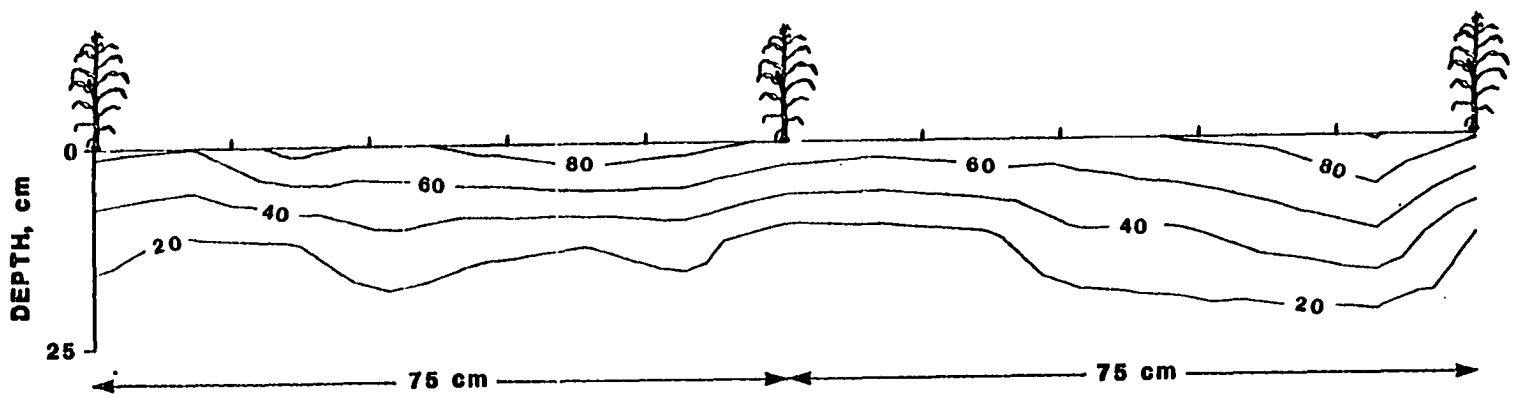

Figure B5. Available phosphorus distribution at Site E, Area I

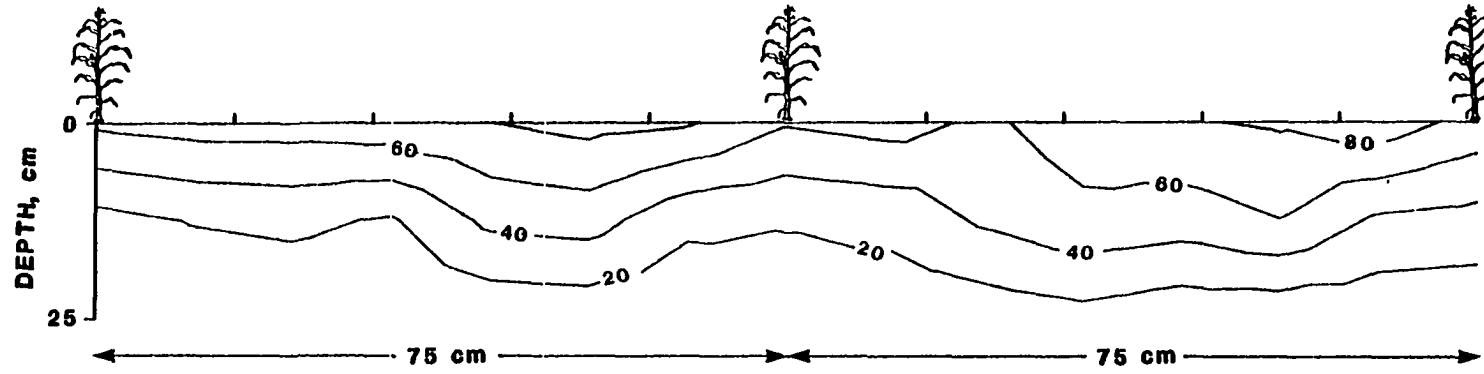

Figure B6. Available phosphorus distribution at Site F, Area I

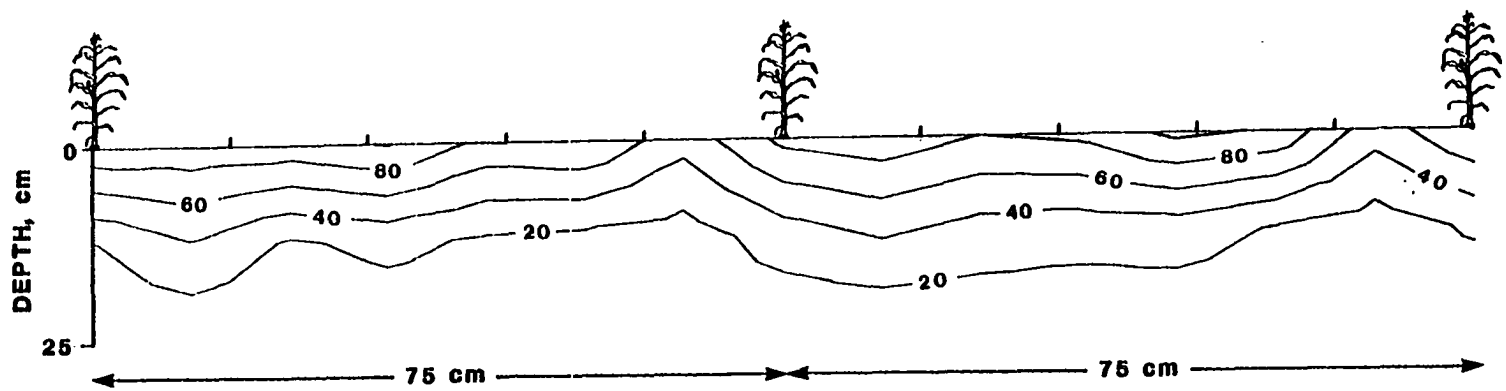

Figure B7. Available phosphorus distribution at Site A, Area II

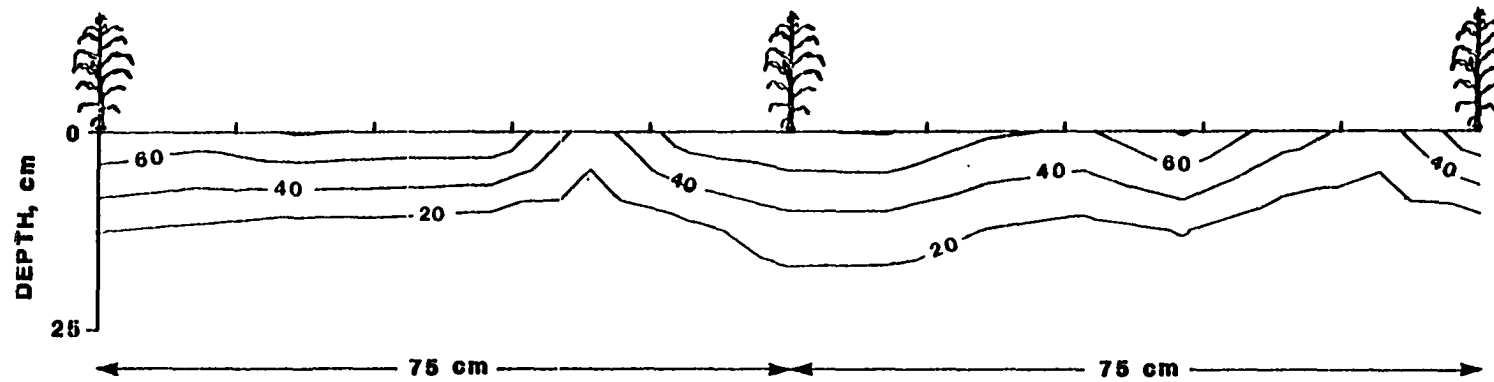

Figure B8. Available phosphorus distribution at Site B, Area II

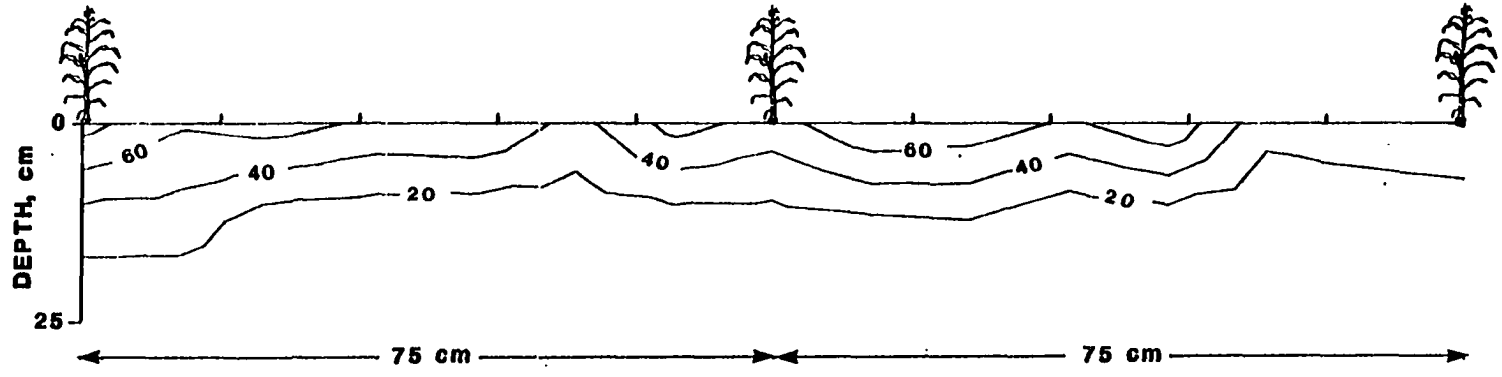

Figure B9. Available phosphorus distribution at Site C, Area II

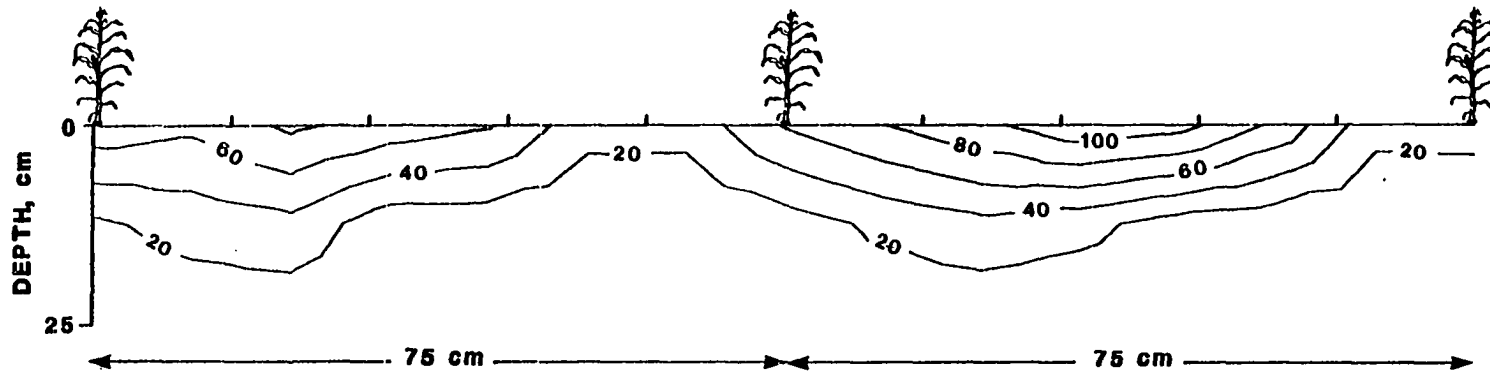

Figure B10. Available phosphorus distribution at Site D, Area II

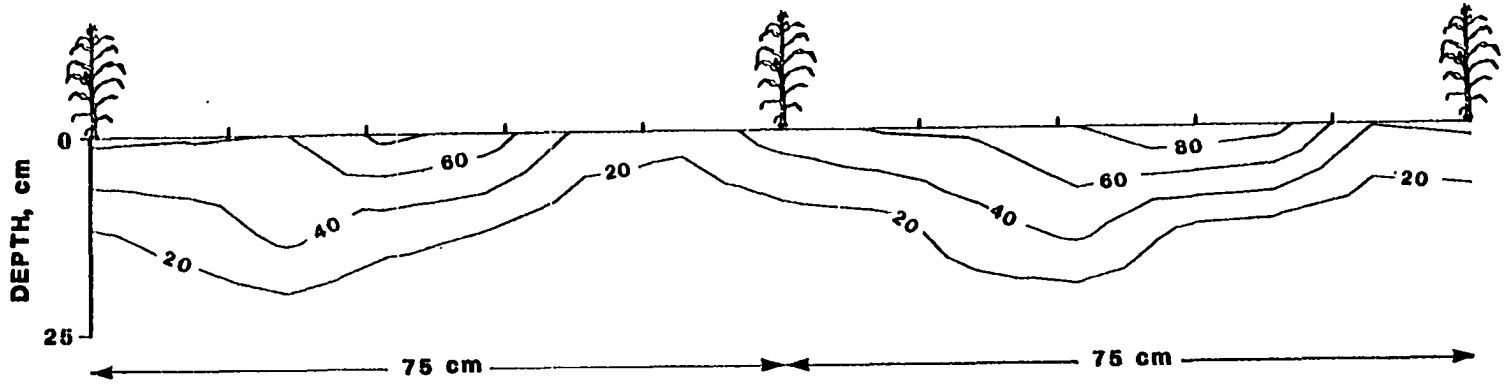

Figure B11. Available phosphorus distribution at Site E, Area II

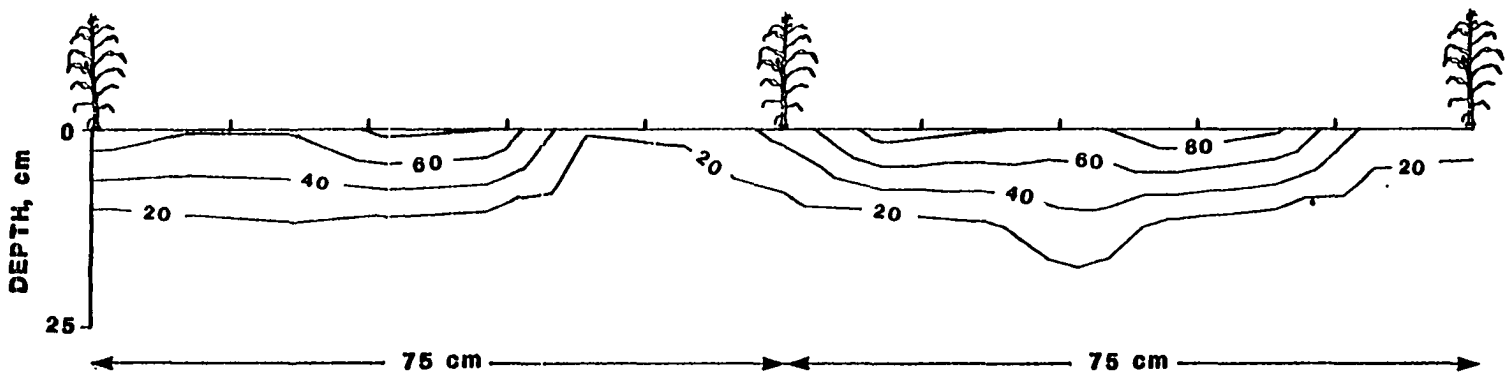

Figure B12. Available phosphorus distribution at Site F, Area II

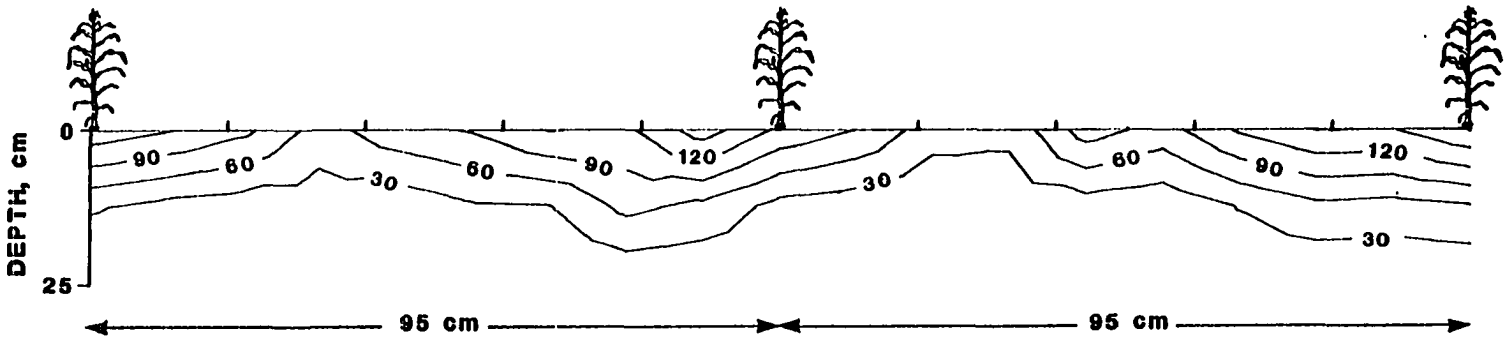

Figure B13. Available phosphorus distribution at Site A, Area III

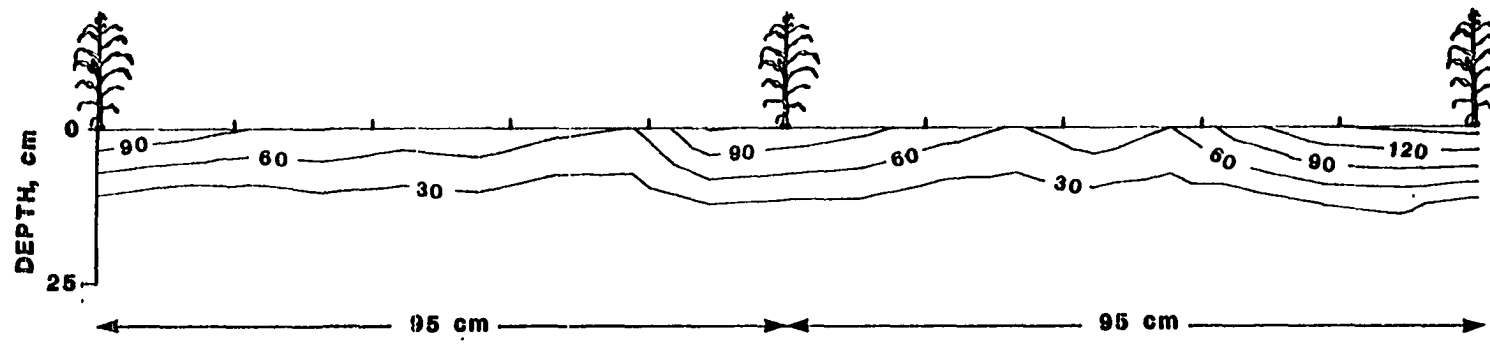

Figure B14. Available phosphorus distribution at Site B, Area III

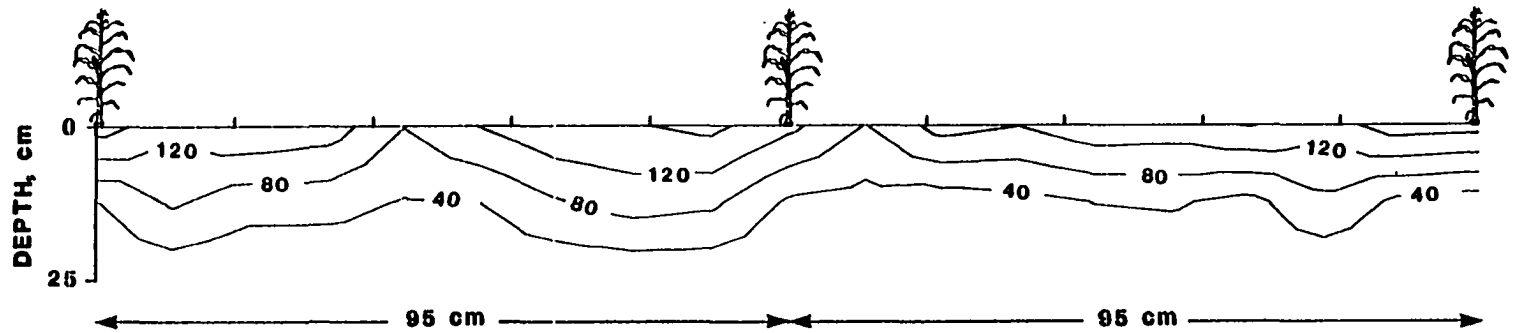

Figure B15. Available phosphorus distribution at Site C, Area III

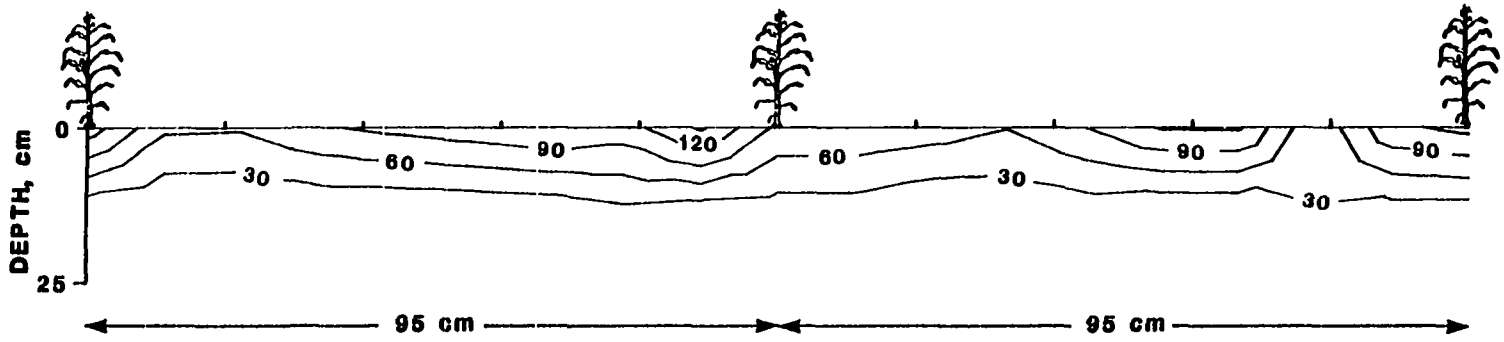

Figure B16. Available phosphorus distribution at Site D, Area III

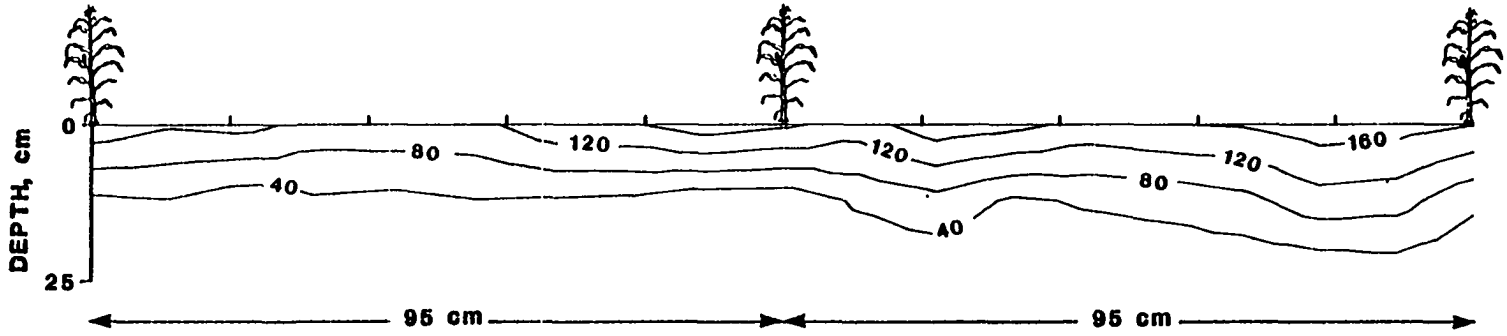

Figure B17. Available phosphorus distribution at Site E, Area III

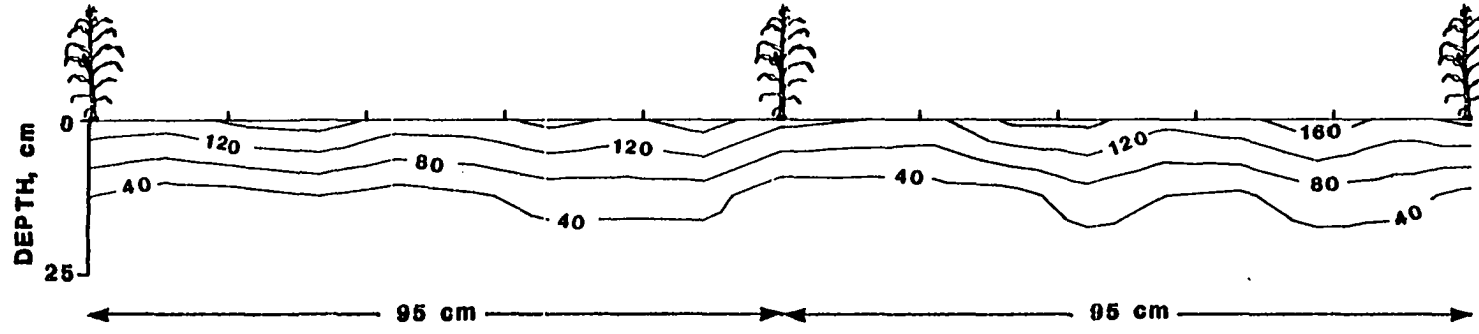

Figure B18. Available phosphorus distribution at Site F, Area III

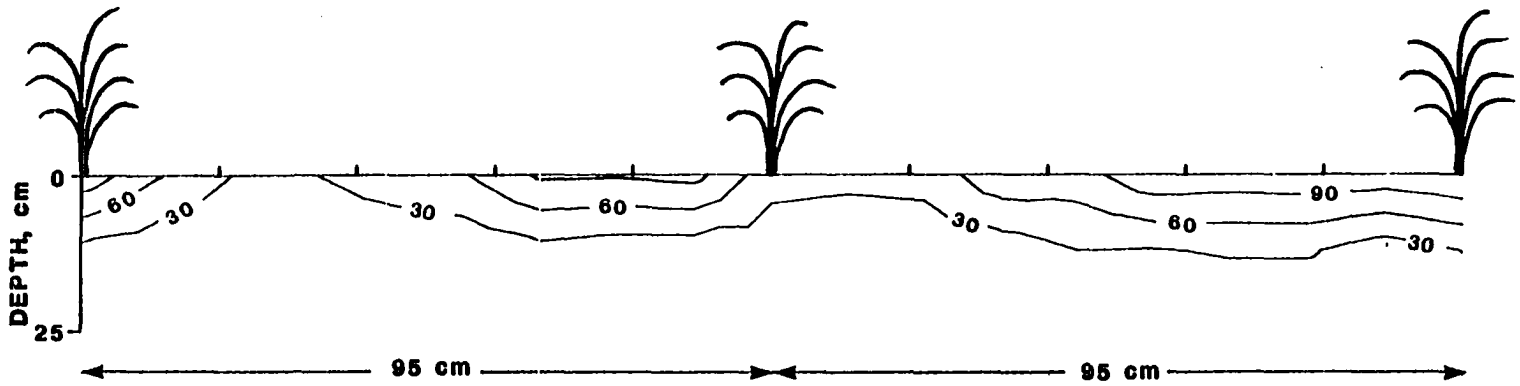

Figure B19. Available phosphorus distribution at Site A, Area IV

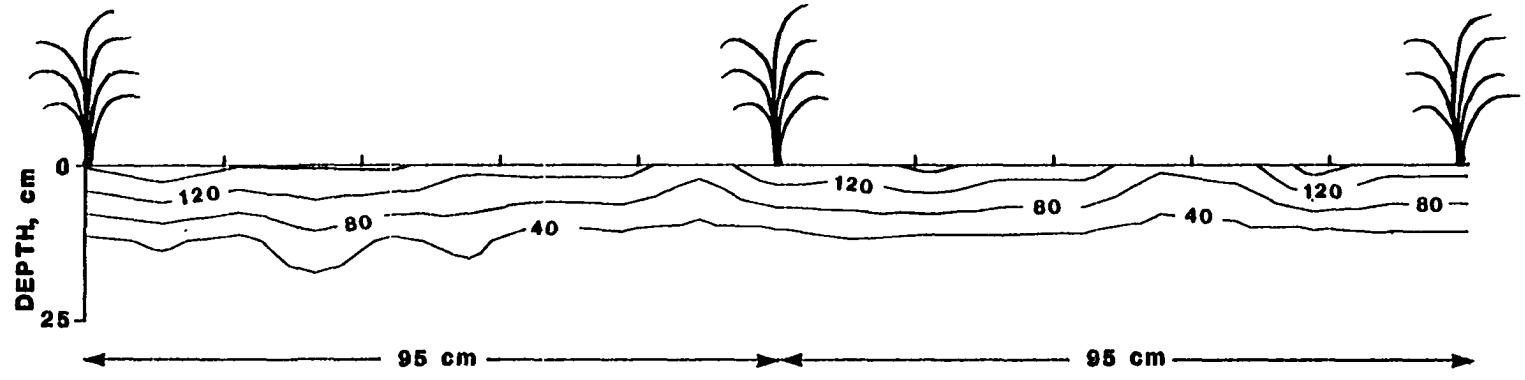

Figure B20. Available phosphorus distribution at Site B, Area IV

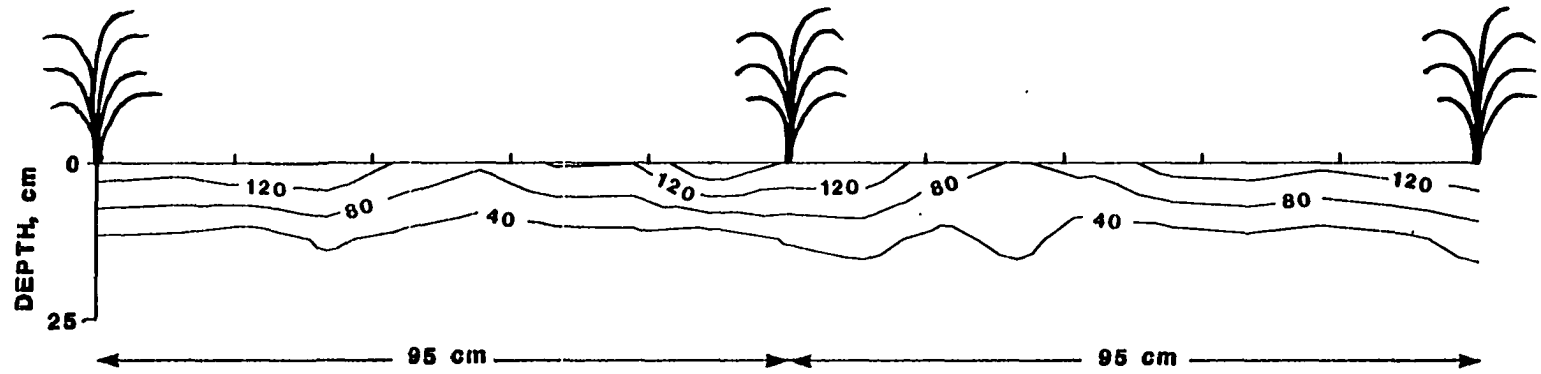

Figure B21. Available phosphorus distribution at Site C, Area IV

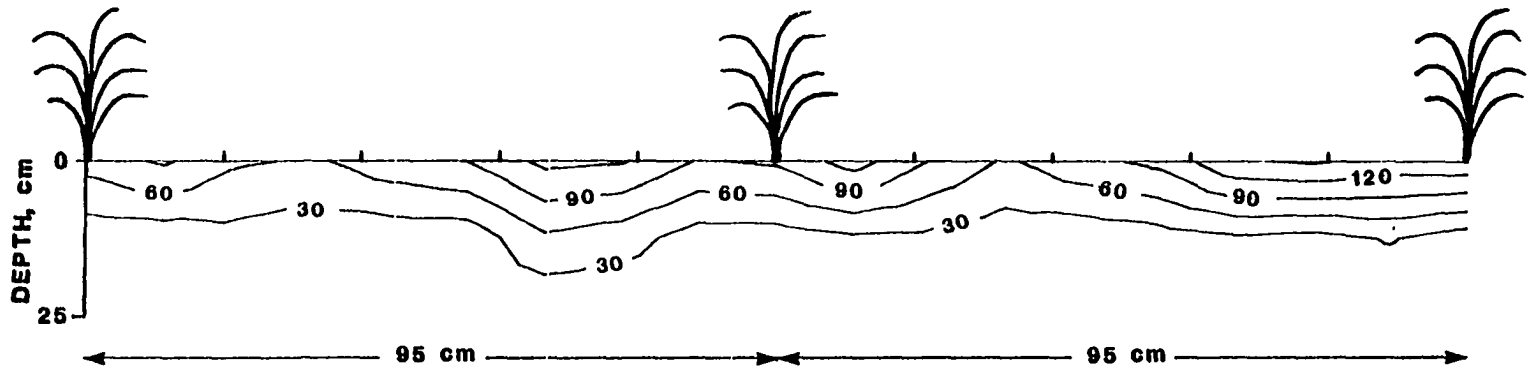

Figure B22. Available phosphorus distribution at Site D, Area IV

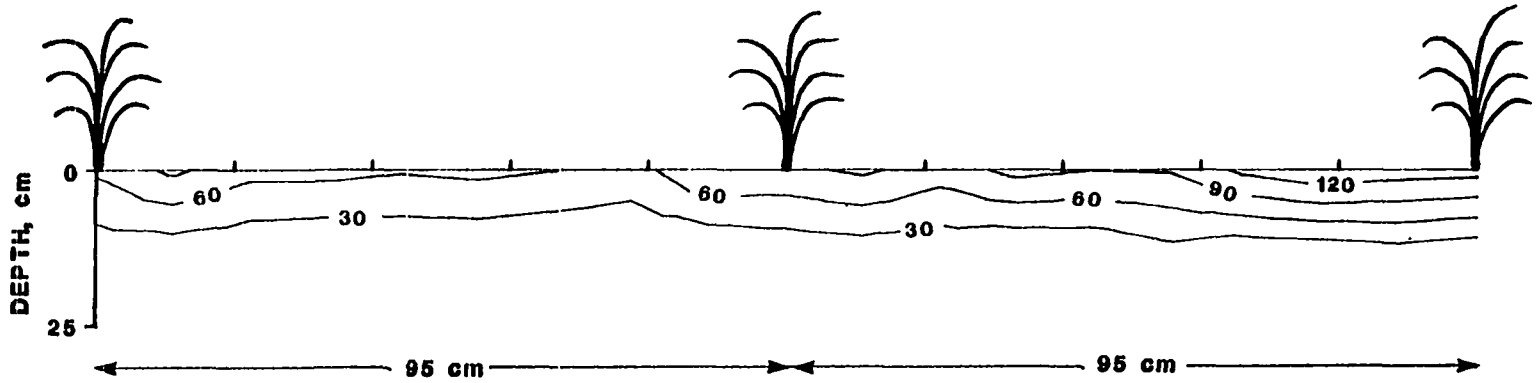

Figure B23. Available phosphorus distribution at Site E, Area IV

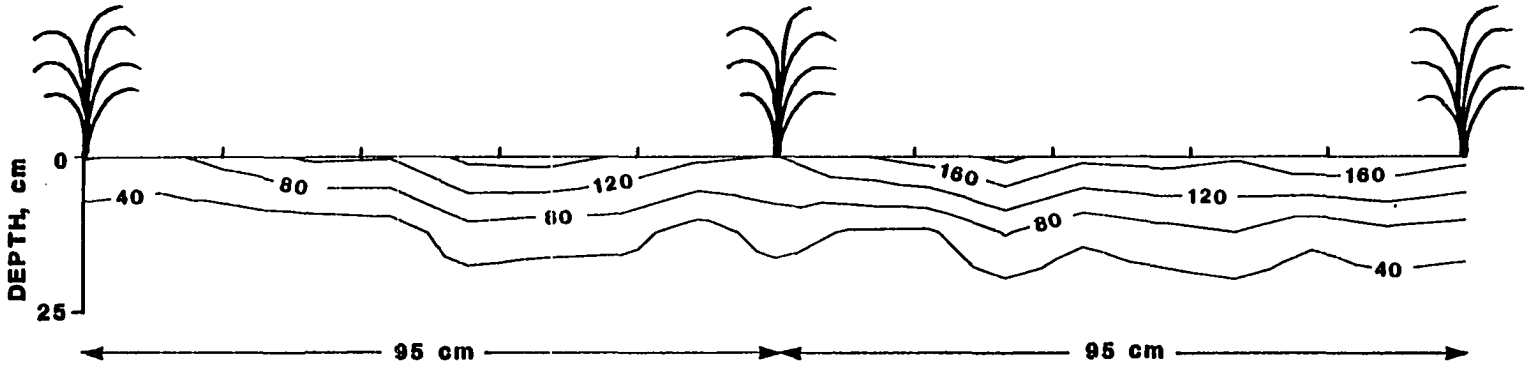

Figure B24. Available phosphorus distribution at Site F, Area IV

APPENDIX C: AVAILABLE POTASSIUM DISTRIBUTIONS

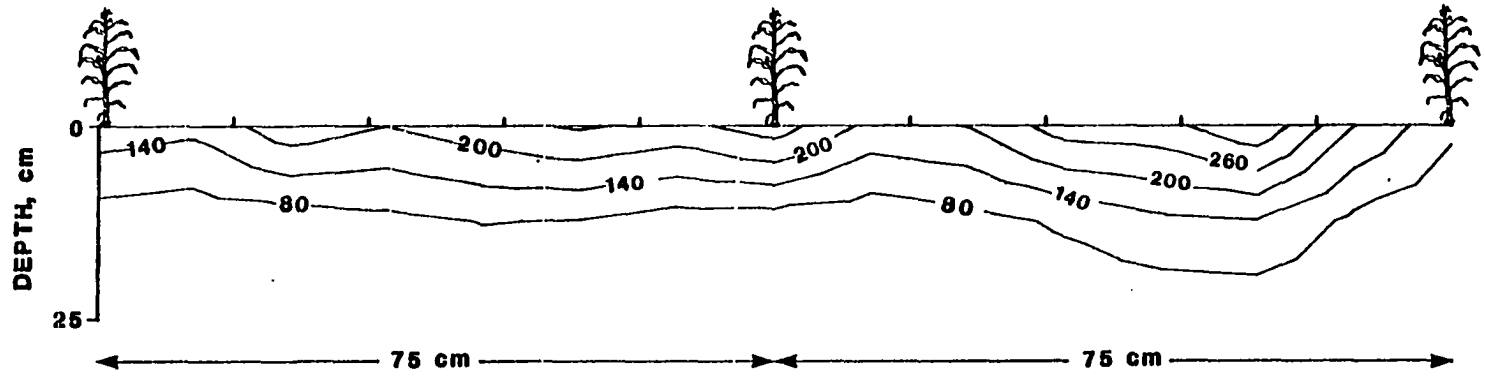

Figure C1. Available potassium distribution at Site A, Area I

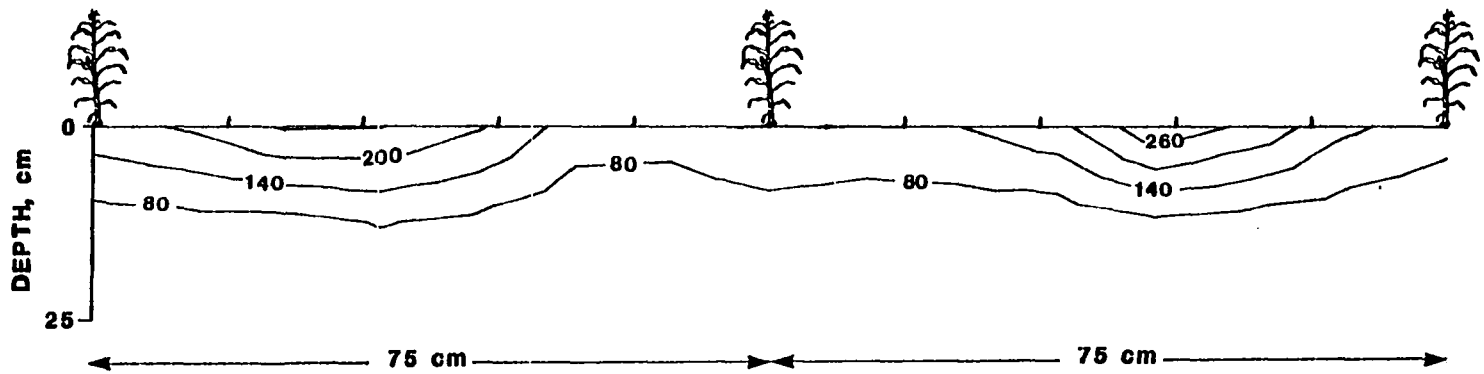

Figure C2. Available potassium distribution at Site B, Area I

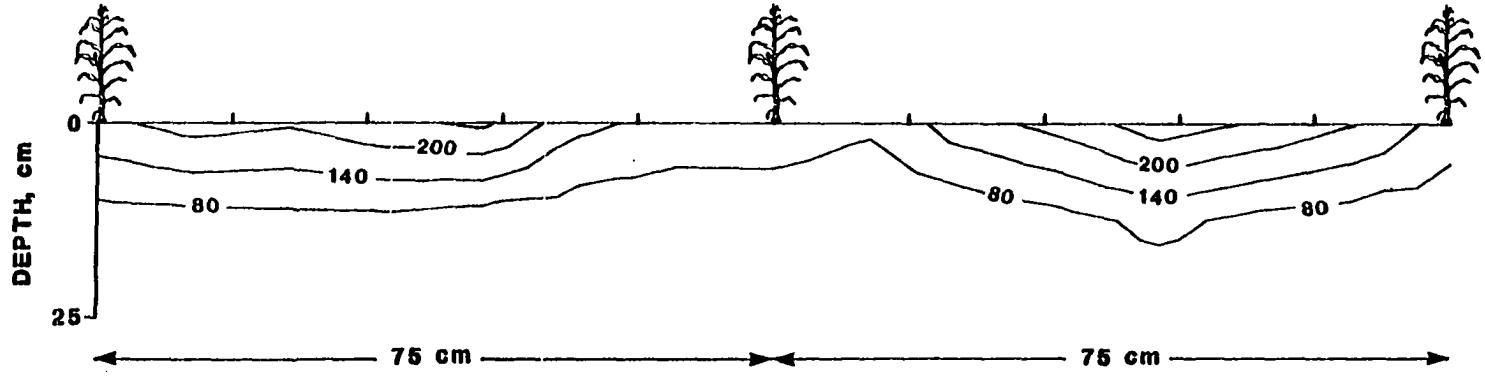

Figure C3. Available potassium distribution at Site C, Area I

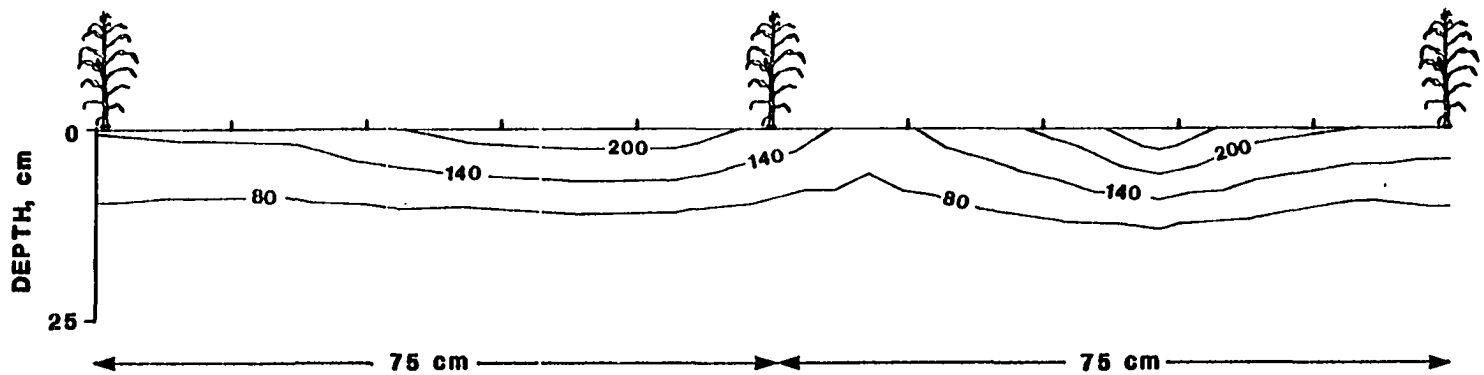

Figure C4. Available potassium distribution at Site D, Area I

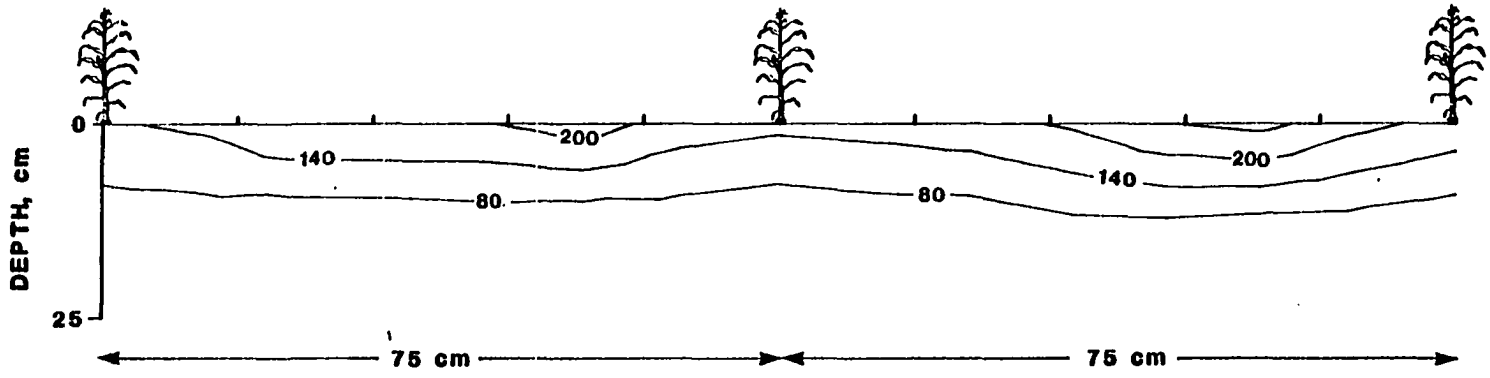

Figure C5. Available potassium distribution at Site E, Area I

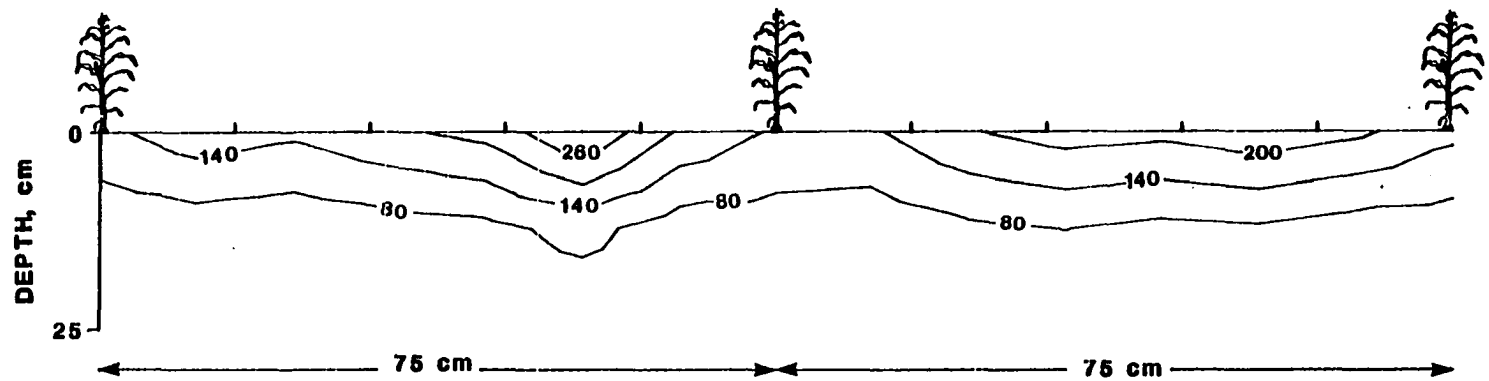

Figure C6. Available potassium distribution at Site F, Area I

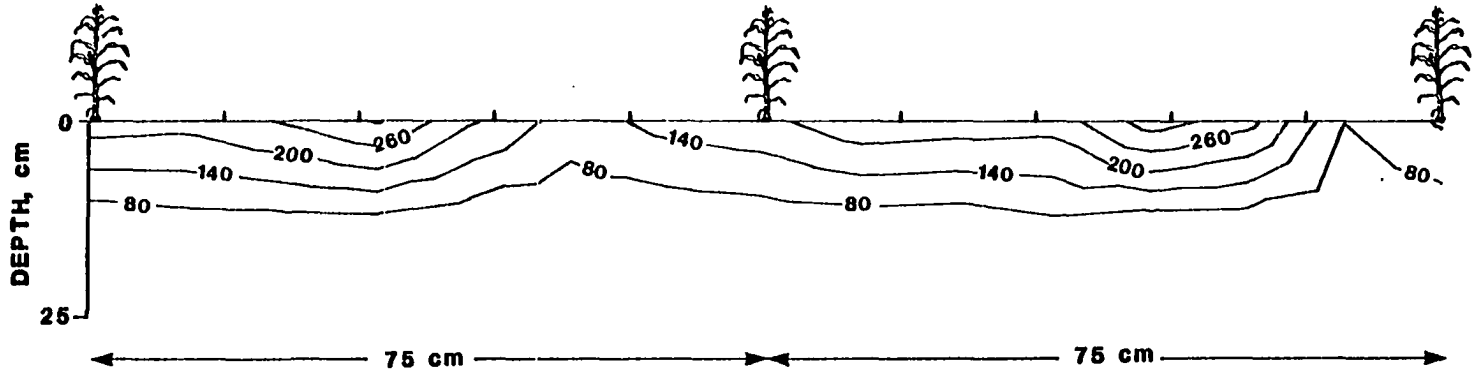

Figure C7. Available potassium distribution at Site A, Area II

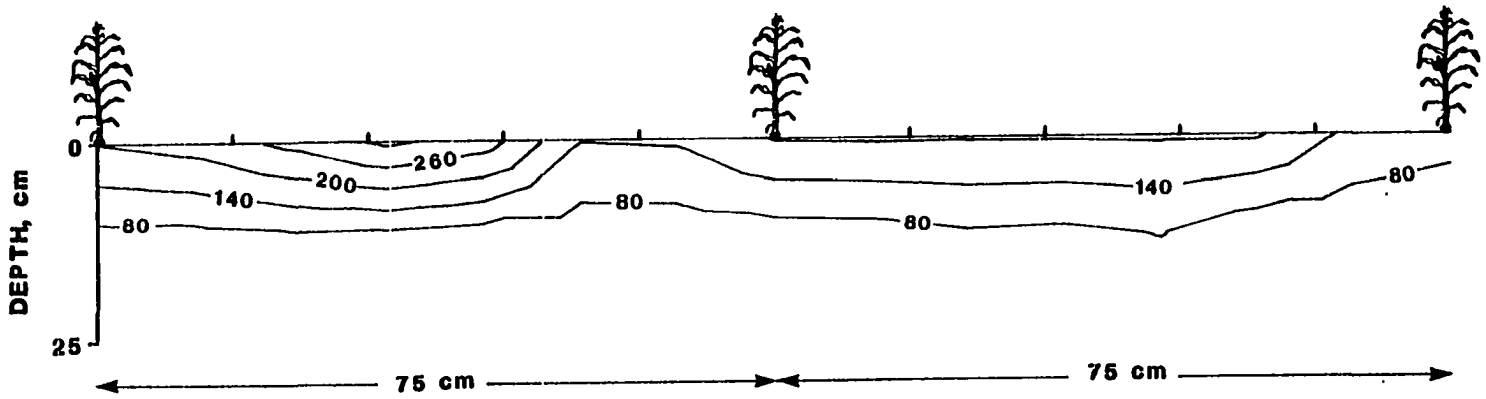

Figure C8. Available potassium distribution at Site B, Area II

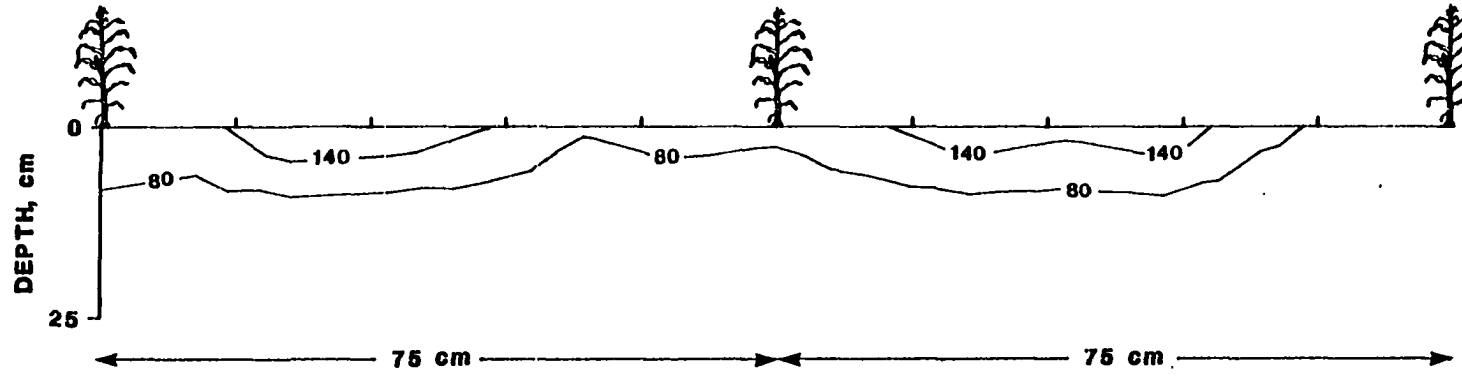

Figure C9. Available potassium distribution at Site C, Area II

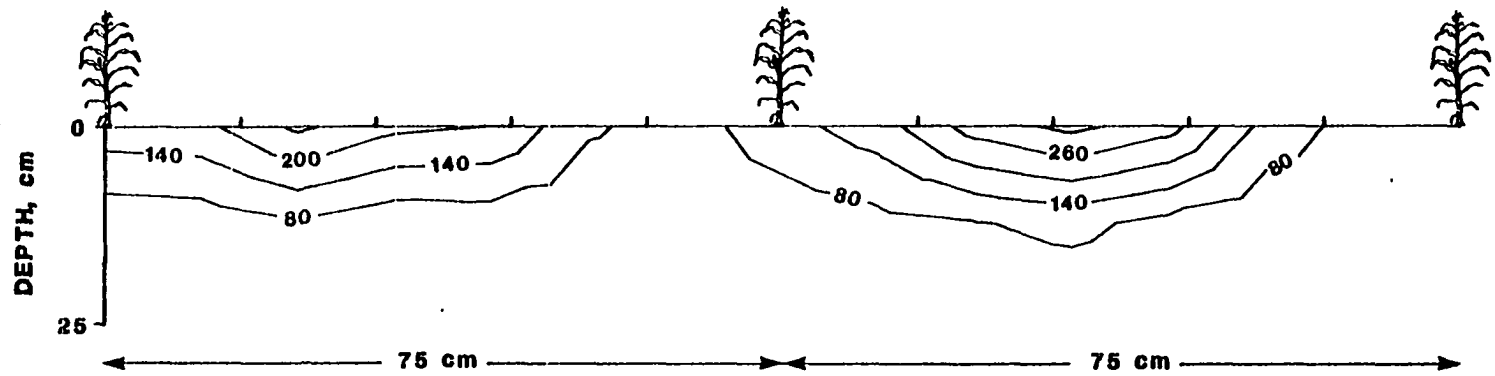

Figure C10. Available potassium distribution at Site D, Area II

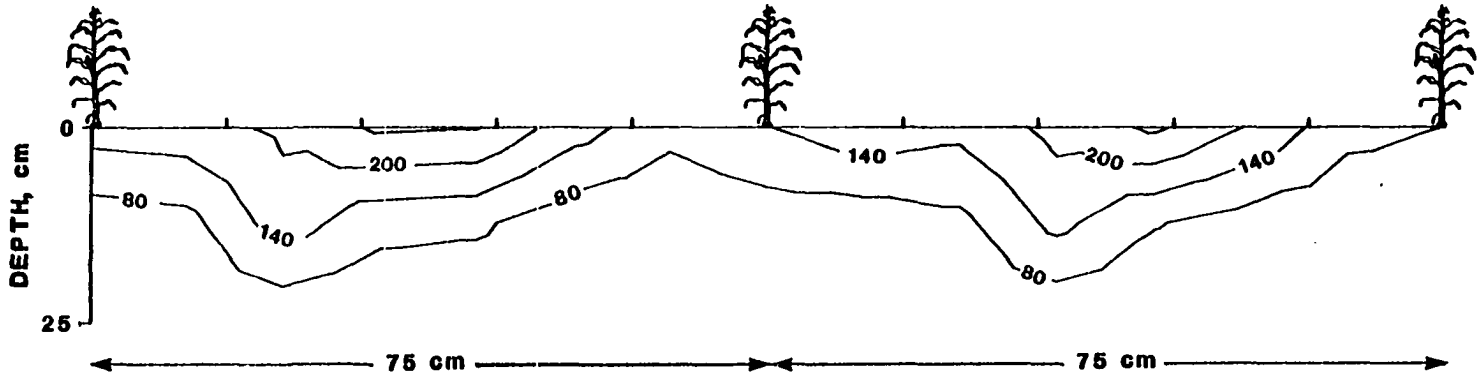

Figure C11. Available potassium distribution at Site E, Area II

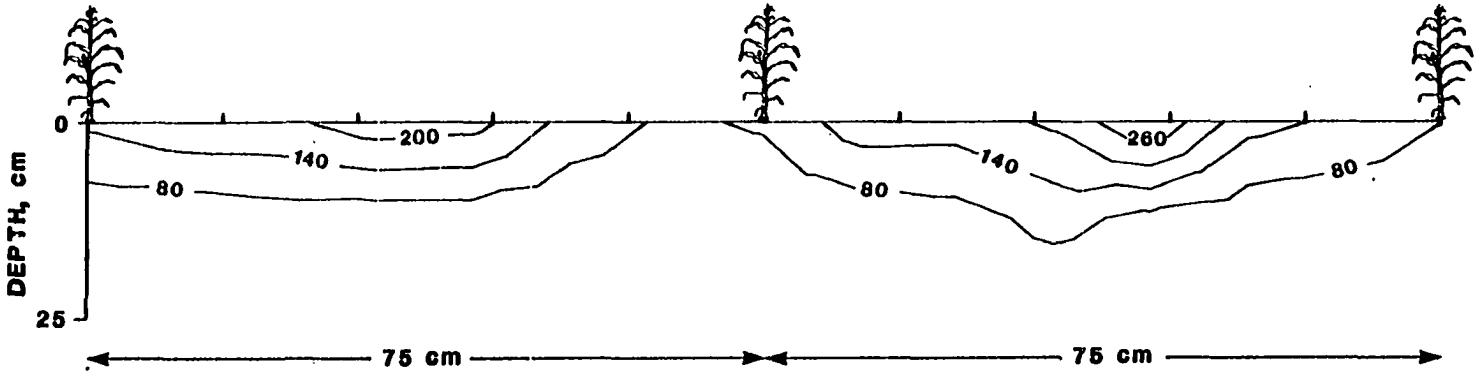

Figure C12. Available potassium distribution at Site F, Area II

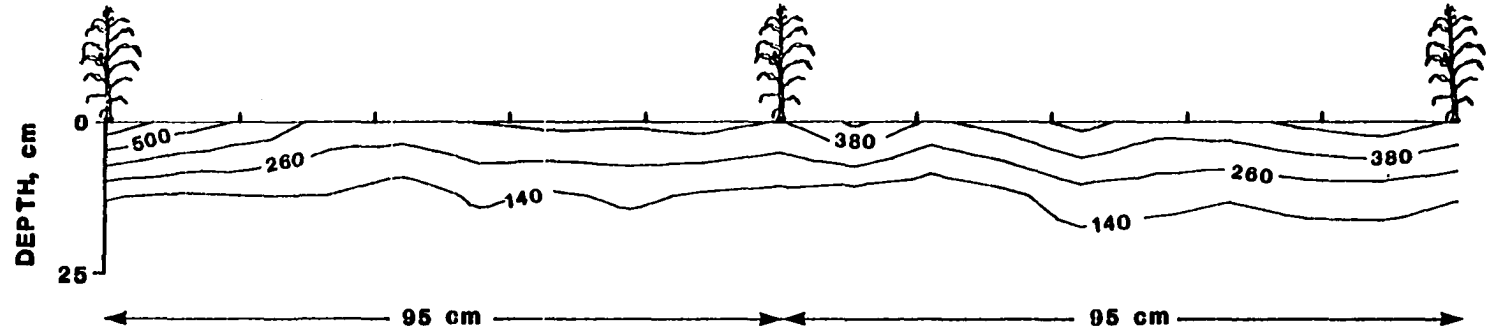

Figure C13. Available potassium distribution at Site A, Area III

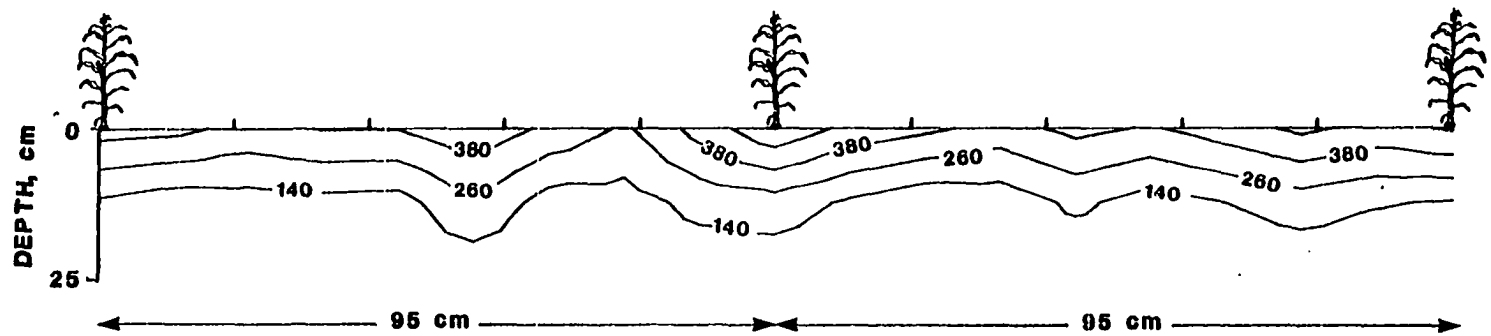

Figure C14. Available potassium distribution at Site B, Area III

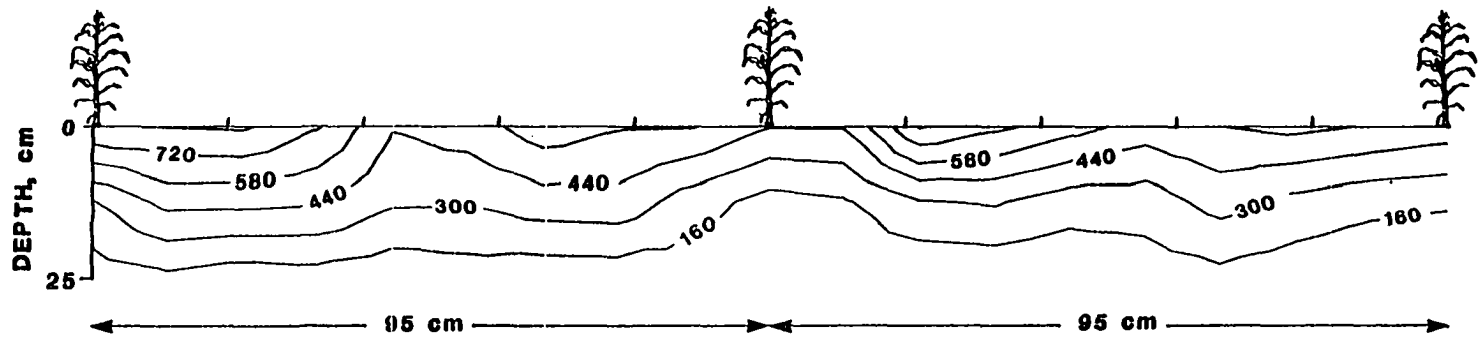

Figure C15. Available potassium distribution at Site C, Area III

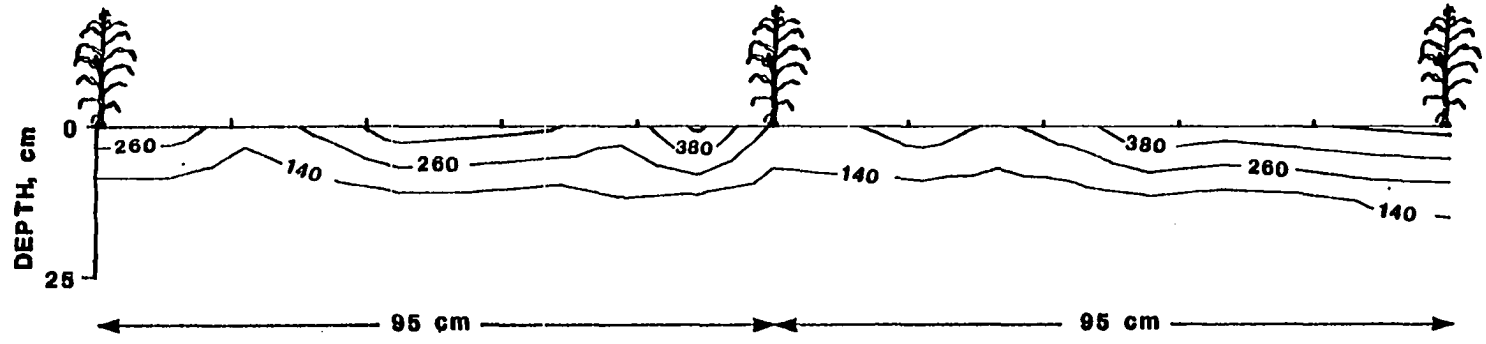

Figure C16. Available potassium distribution at Site D, Area III

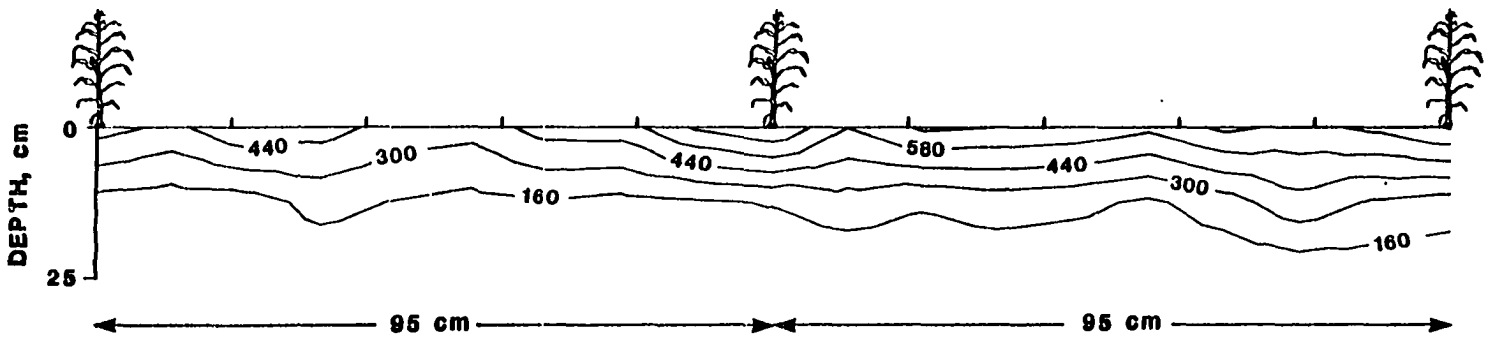

Figure C17. Available potassium distribution at Site E, Area III

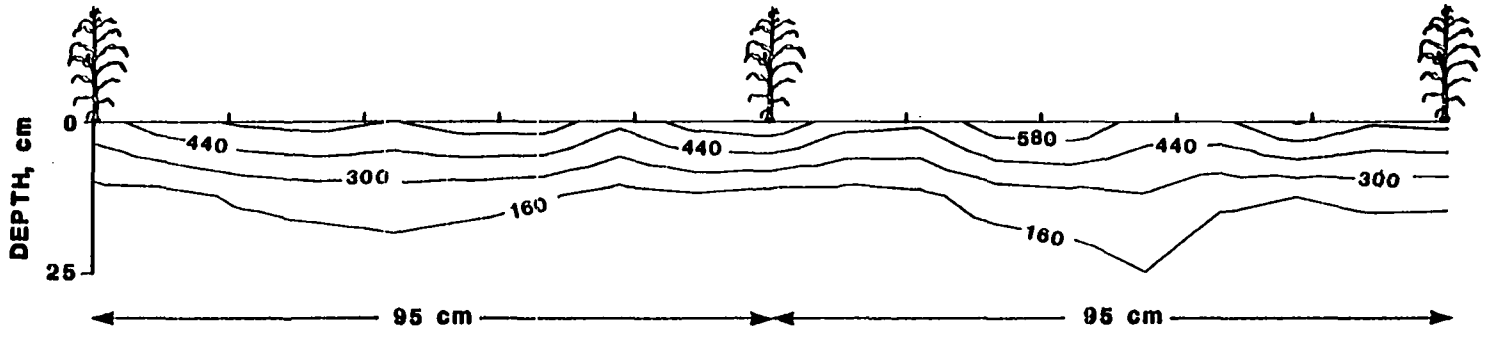

Figure C18. Available potassium distribution at Site F, Area III

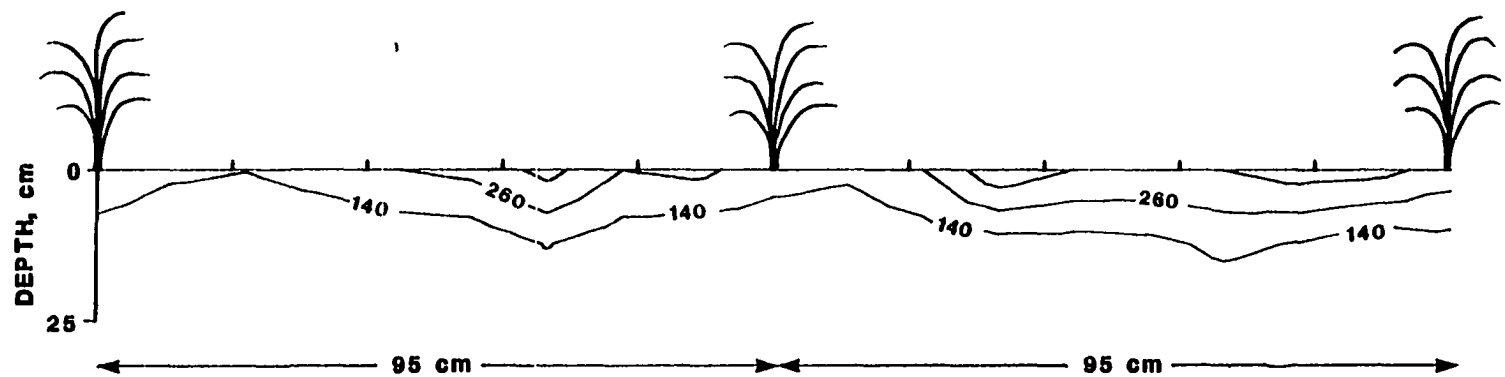

Figure C19. Available potassium distribution at Site A, Area IV

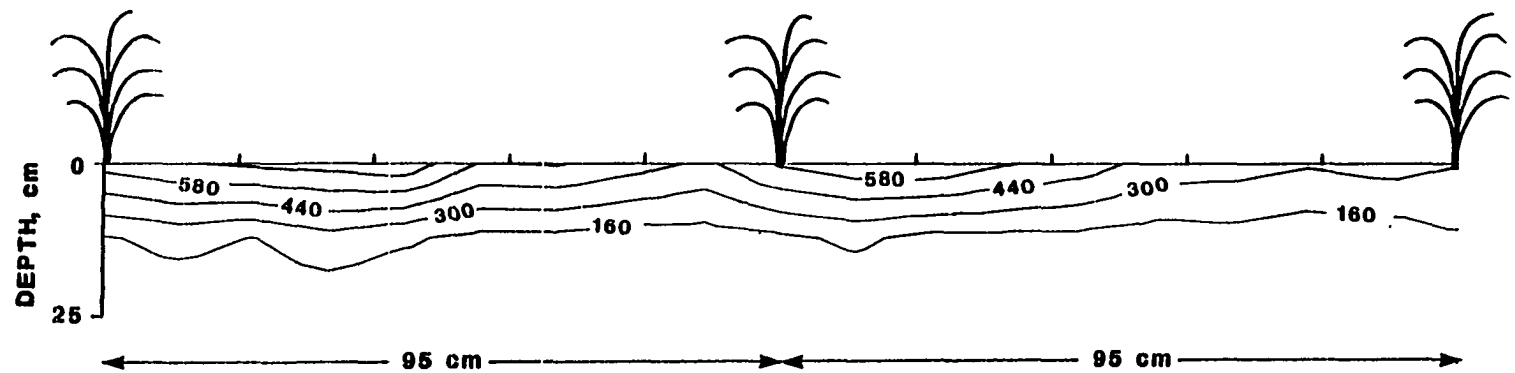

Figure C20. Available potassium distribution at Site B, Area IV

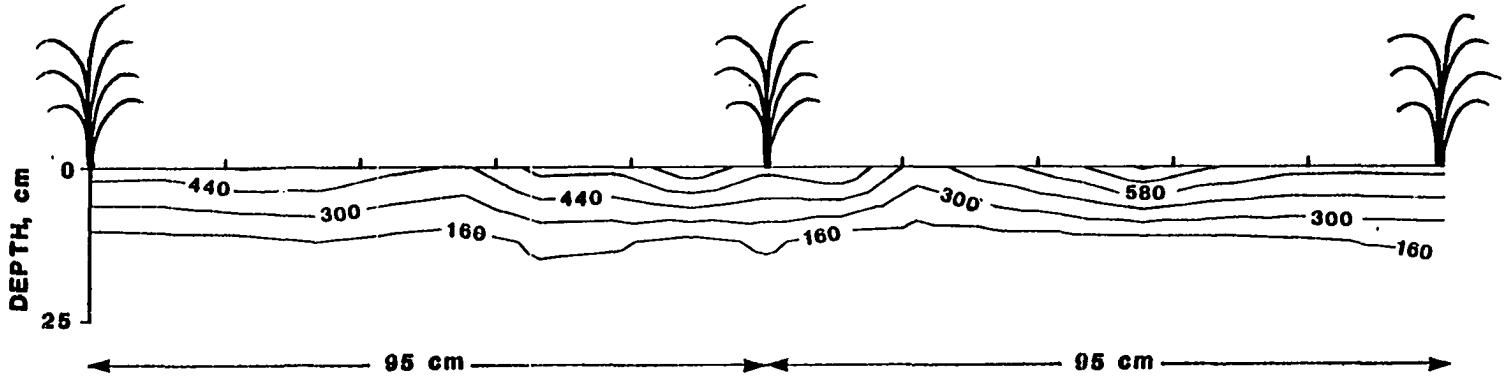

Figure C21. Available potassium distribution at Site C, Area IV

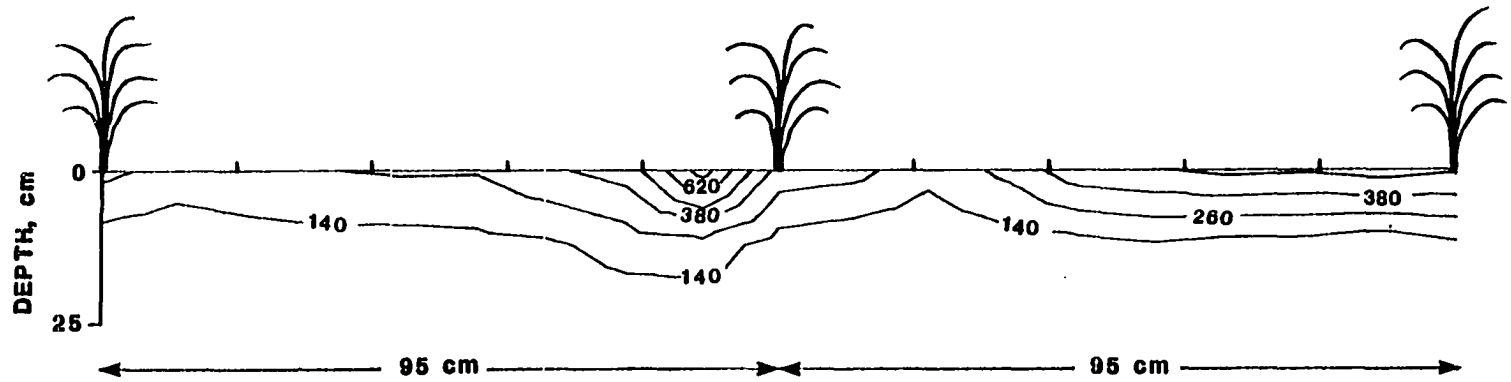

Figure C22. Available potassium distribution at Site D, Area IV

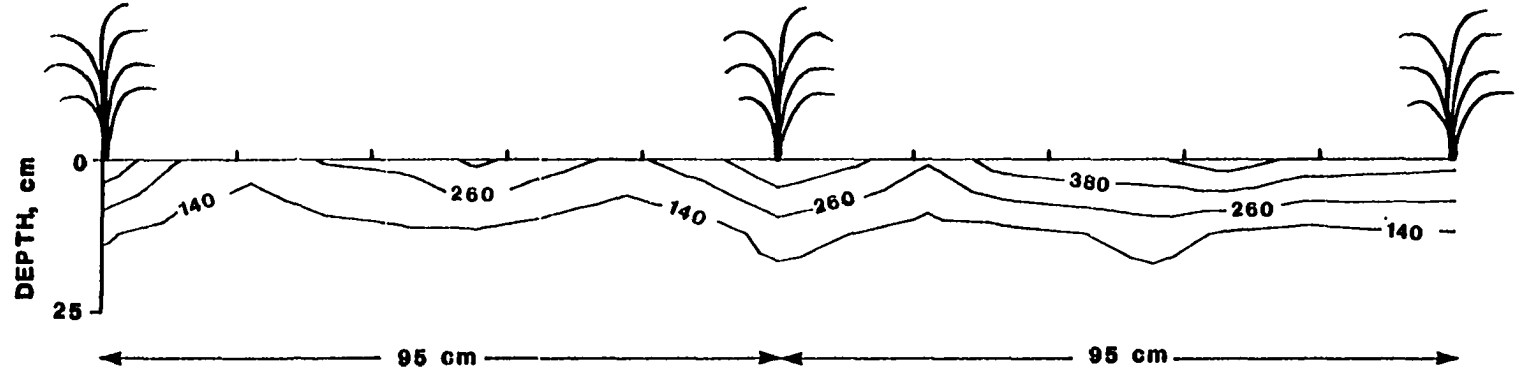

Figure C23. Available potassium distribution at Site E, Area IV

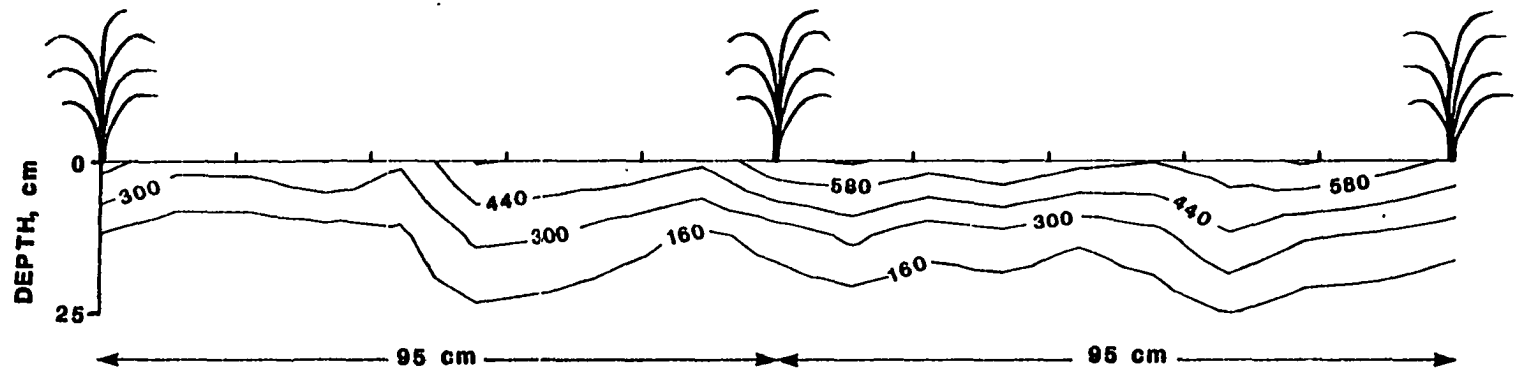

Figure C24. Available potassium distribution at Site F, Area IV